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RESEARCH ARTICLE **RENEWABLE ENERGY**

Design and Implementation of a Remotely Monitored Hybrid Renewable Energy System (Solar–Wind) with IoT-Based Relay Control and Real-Time Data Logging

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ABSTRACT

This paper presents a cost-effective smart hybrid renewable energy system (HRES) that integrates solar PV and wind energy systems and supports VRLA battery systems and DC loads. Stand-alone renewable energy systems are subject to intermittence. The design proposed in this paper addresses this issue by integrating both renewable energy systems using a four-channel relay board with an embedded electrical interlock that prevents simultaneous dual-source injection to a PWM charge controller and maintains solar energy priority. The control unit was an Arduino Mega 2560. It read the voltage and current of the PV, wind, and battery systems through the ACS712 Hall effect sensors and B25 voltage dividers, and established a solar-priority interlock. The interlock was improved by remote relay control through the MQTT protocol. The system logged data every 10 seconds in CSV format, displayed information on a 20 × 4 I²C LCD, and sent data wirelessly with the ESP8266 module to a MIT App Inventor mobile application via MQTT. Two test sessions were conducted. Session B (January 16, 2026) was an early validation test. Session C (March 13, 2026) was the main test and was conducted after the sensors were replaced and recalibrated. The combined-source load test (2.83 minutes) was conducted with a mean load power of 25.70 W and a single-sample peak of 26.79 ± 1.5 W (99.2 ± 5.6 % of the rated load). The maximum solar and wind powers were 34.36 W and 10.05 W, respectively. Following the implementation of necessary corrective measures, the relay and measurement consistency for both wind and output was 100%, confirming that the interlock and control logic performed as designed.

تصميم وتنفيذ نظام هجين للطاقة المتجددة (شمسي – رياحي) يخضع للمراقبة عن بُعد، مع تحكم في المرحلات قائم على إنترنت الأشياء وتسجيل البيانات في الوقت الفعلي

ابراهيم امبية[1,*]، يوسف أدريدر[1]، عبدالرحيم أمبارك[1]، أيوب شرف الدين[1]، ياسر نصار[2]، محمد خليل[3]، منعم المنفي[4]، هالة الخزندار[5]

الكلمات المفتاحية

الطاقة الشمسية
طاقة الرياح
أردوينو ميقا 2560
وحدة التحكم في الشحن PWM
بروتوكول MQTT
إنترنت الأشياء، أجهزة الاستشعار
بطاقة SD

الملخص

تقدم هذه الورقة نظامًا هجينًا ذكيًا للطاقة المتجددة فعالاً من حيث التكلفة، يدمج أنظمة الطاقة الشمسية الكهروضوئية وطاقة الرياح، ويدعم أنظمة بطاريات VRLA والأحمال التي تعمل بالتيار المستمر. وتتعرض أنظمة الطاقة المتجددة المستقلة لمشكلة التقطع. ويعالج التصميم المقترح في هذه الورقة هذه المشكلة من خلال دمج كلا نظامي الطاقة المتجددة باستخدام لوحة ترحيل ذات أربع قنوات مزودة بقفل كهربائي مدمج يمنع التغذية المتزامنة من مصدرين إلى وحدة التحكم في الشحنPWM ، ويحافظ على أولوية الطاقة الشمسية. كانت وحدة التحكم عبارة عن .Arduino Mega 2560 حيث قامت بقراءة الجهد والتيار لأنظمة الطاقة الكهروضوئية وطاقة الرياح والبطاريات من خلال مستشعرات تأثير هول ACS712 ومقسمات الجهدB25 ، وأنشأت نظام قفل يعطي الأولوية للطاقة الشمسية. وتم تحسين نظام القفل هذا من خلال التحكم عن بُعد في المرحلات عبر بروتوكول .MQTT كان النظام يسجل البيانات كل 10 ثوانٍ بتنسيقCSV ، ويعرض المعلومات على شاشة LCD I²C مقاس 20 × 4، ويرسل البيانات لاسلكيًا باستخدام وحدة ESP8266 إلى تطبيق جوال MIT App Inventor عبر بروتوكول MQTT. أُجريت جلستا اختبار. كانت الجلسة ب (16 يناير 2026) اختبارًا أوليًا للتحقق من الصحة. أما الجلسة ج (13 مارس 2026) فكانت الاختبار الرئيسي وأُجريت بعد استبدال أجهزة الاستشعار وإعادة معايرتها. أُجري اختبار الحمل من مصادر مجمعة (2.83 دقيقة) بمتوسط طاقة حمل قدره 25.70 واط وقيمة ذروة لعينة واحدة بلغت 26.79 ± 1.5 واط (99.2 ± 5.6 % من الحمل المقنن). وبلغت القوى القصوى للطاقة الشمسية وطاقة الرياح 34.36 واط و10.05 واط على التوالي. وبعد تنفيذ الإجراءات التصحيحية اللازمة، بلغت دقة الترحيل والقياس لكل من طاقة الرياح

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والإنتاج 100٪، مما يؤكد أن منطق التداخل والتحكم قد أدى وظيفته كما هو مصمم.

Introduction

In light of the current rise in global demands for electricity due to increased industrialization and population growth, The global electricity generation in 2024 reached approximately 30,850 TWh (30.85 PWh) [1-3]. With fossil fuels (coal, gas, oil) providing about 58%, renewables (hydro, wind, solar, bio, geo) around 32%, and nuclear around 10%. These energy sources currently are under threat because they contribute significantly to GHG emissions, including carbon dioxide (CO_2). [4-12], this is because GHGs exacerbate climate change and environmental pollution [13,14]. Moreover, fluctuations in the costs of fuel around the globe have forced companies to consider renewable energy sources to make sure that all options available remain economically stable [15,16]. Renewable energy technologies would be best suited for this purpose [17-31]. In the end of 2025, the global installed capacities of renewables such as solar energy (PV, thermal and concentrated solar power) [32-54], wind [55-67], bioenergy [68-81], etc., reached about 4,448.1 GW, from them 2,200 GW for PV solar energy systems, 1,320 GW for wind energy, and the total cumulative biopower capacity reached 151 GW. Integrating multi-sources of energy are excellent since they occur in abundance and are affordable to turn into useful forms of energy [82-92]. Lastly, utilizing different energy sources together with energy storage technologies, such as batteries, pumped hydropower energy storage, fuel cells, compressed air storage will eliminate their intermittency issues [93-119]. For this reason, there is an urgent need for the utilization of techno-economic modeling in optimizing power systems [120-134]. In 2025, renewable electricity surpassed coal for the first time, accounting for 34.3% of global electricity, compared to coal's 33.1% [135]. The renewable share will be close to 43% by 2030, driven by the continual decrease in the price of solar and wind technologies [136]. This, of course, does not mean greater global generation translates to reliable electricity in regions with the greatest supply problems [137-140]. These are the areas where hybrid systems are most relevant [141-151]. Intermittency is the fundamental engineering challenge of most of these systems. Solar power goes to zero after sunset and is further diminished with cloud cover, while wind output is erratic and highly variable from day to day and season to season. The daily variation in output between the two is actually beneficial when both are integrated into a system. When one of the two is generating insufficient supply, the other is expected to cover the gap. This combination and integration of the two technologies greatly reduces the reliance on them while improving supply.

Libya is a great case study for this approach. It is not a strong theoretical example for a case study. However, given the strong resource conditions, it is very good measurement-wise. It is located between 20° and 33°N, has an annual solar irradiation of over 2,500 kWh/m², and has coastal winds of 5–8 m/s [152-160]. The above makes a strong case for the integration of hybrid wind and solar systems. The local application of this concept is greatly lacking documented low-cost prototypes of this nature with integrated smart systems.

This research integrates many aspects from previous projects. PV–wind HRES reviews focused on storage integration, EMS frameworks, and the strategies and methods for the management of intermittency that enable the safe and reliable off-grid operation [161-168]. Studies on system topology and hybrid systems design and optimization identified the efficiency trade-offs [169,170]. It was also shown that DFIG-based control could provide an edge to balance the output in the presence of variable resources [171]. For the monitoring layer, works on residential smart solar systems [172] and MQTT-based power system monitoring [173] provide very robust implementation examples [174]. The closest example to date is an Arduino-based off-grid hybrid for which source switching was done by relays, and logging was done with Arduino [175,176]. A follow-up work also established that the same function can be done with low-cost microcontrollers in a real-time energy optimization scenario [177]. This study advances the aforementioned concepts by incorporating wireless communication, multi-channel sensing, and Kalman-filtered measurements all in one system.

The study gives the full design, implementation and testing of an Arduino Mega 2560 controlled solar-wind HRES with the following hardware: an electrically interlocked relay board for safe source switching, Kalman-filtered ACS712 sensors with front end circuitry for voltage and current measurement, real time logging on SD-cards with an RTC, local display of 20x4, and wireless MQTT communication to a custom mobile application, all in an integrated low-cost system. out. The electrical interlock and the solar-priority source-priority interlock rule, first, together prevent simultaneous dual-source injection, while keeping the control rules simple enough for inspection and modification. Second, in practice, it was necessary to use a Kalman filter for the ACS712 Hall-effect sensors, instead of using their raw output. The results of Session B were not reliable until the sensors were replaced and the filter was properly tuned. Third, the three-tier monitoring architecture (LCD, SD card, MQTT app) is completely documented and reproducible on commodity hardware. Fourth, the experimental sessions of the two experiments include not only clean performance data but also a sensor fault episode, the corrective action, and the verification after correction, an experimental transparency that is often missing in prototype studies. Section II describes the system architecture and the hardware. Section III describes the firmware, control algorithm, and IoT layer. Section IV presents and discusses the experimental results of this study. Section V concludes the paper and identifies directions for further development.

Methodology and Materials

System Architecture Overview

The system is based on a DC-coupled bus architecture. The PV array and wind source are rectified to AC and then supplied to the latter, and the DC-DC voltage step-up is fed to the input terminal of a PWM solar charge controller through the mutually exclusive relay contacts. Figure 1 shows a full schematic of all power and signal paths.

Hardware Components

The sensor data was read, and the relay channels were commanded by an Arduino Mega 2560, which served as the central controller. The ESP8266 Wi-Fi module handles the MQTT communication by itself, so the network overhead is taken out of the main control loop. On the Arduino ADC

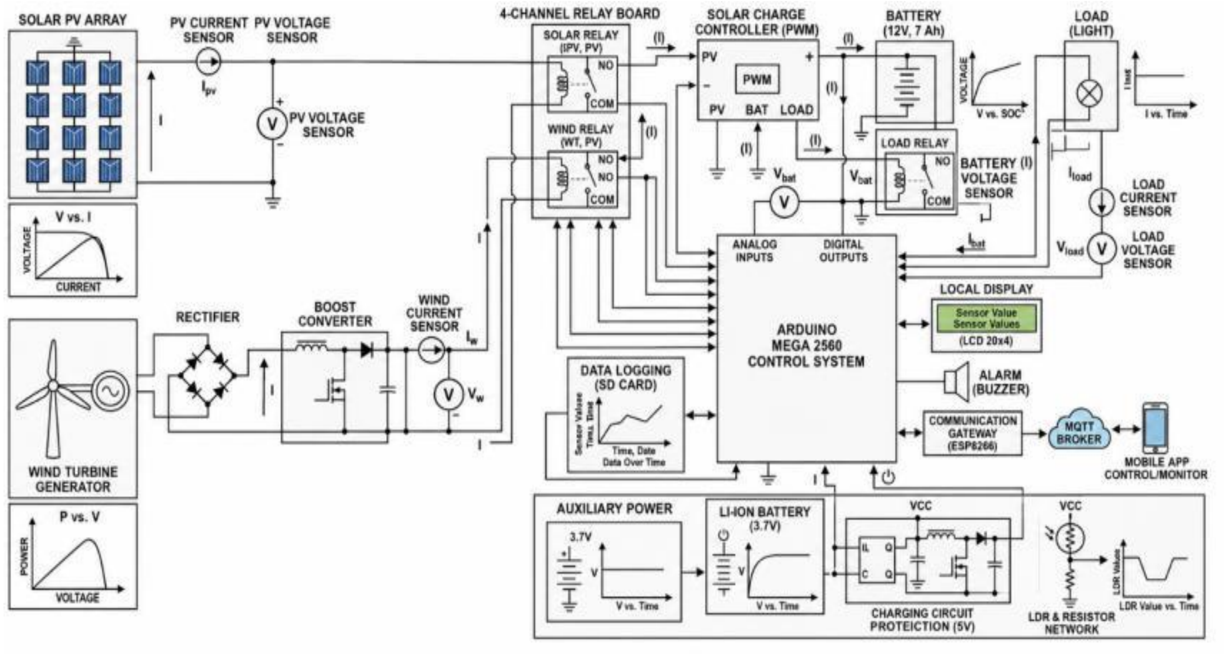

Figure 1: Hybrid Solar–Wind Power System Schematic Diagram

side, pins A0–A3 read the four ACS712 current channels (wind, solar, battery and output), pins A4–A7 read the corresponding voltage channels via B25 voltage-divider modules, pin A8 monitors the internal DC bus and pin A9 is connected to an LDR in a voltage-divider network providing a rough qualitative read of ambient irradiance.

The 5 V, Active-Low, four-channel optocoupler-isolated relay module was powered from the 5 V rail. Control inputs were mapped to digital outputs D22 (RY_W, wind relay), D23 (RY_PV, solar relay), D24 (RY_BAT, battery relay) and D25 (RY_LOAD, load relay). In the firmware implementation, a LOW signal enables each channel. Communication between Arduino and ESP8266 is done via serial, using the Mega's hardware Serial1 port (TX1 / RX1). The TX & RX pins are cross-connected. TX1 (Mega) -> RX (ESP8266) RX1 (Mega) <- TX (ESP8266) The 20×4 I²C LCD display and the DS1307 RTC module are connected to the same I²C bus (SDA = D20, SCL = D21). The SD card module communicates with the Mega via the SPI interface (MOSI = D51, MISO = D50, SCK = D52, CS = D53) and uses a level shifter to be compatible with 5 V. The hardware configuration is shown in Figure 2.

Solar PV Source

Solar generation came from a monocrystalline ENARAH ESPMC040 panel, rated 40 W at standard test conditions (AM1.5, 1,000 W/m², 25 °C) — Vmp = 18.3 V, Imp = 2.19 A, Isc = 2.32 A, Voc = 22.7 V. Since Vmp sits above the 12 V battery charging voltage, the panel connects straight into PWM-regulated charging with no extra conversion stage needed. Full specifications are in Table 1.

Wind Energy Source

Wind generation was simulated rather than measured from a field turbine — an ASKWA DC motor (24 V, 2 A) with fan blades bolted on, the closest stand-in available in the lab. A four-diode full-bridge rectifier fixes output polarity regardless of shaft direction, and a DC-DC boost converter pushes the result up to roughly 20 V at up to 2 A before it reaches the relay stage. That keeps the wind channel under the PWM controller's 50 V ceiling and, just as importantly, interchangeable with the PV channel in software.

Figure 2: Block-Level Architectural Overview of the hardware configuration PV–Wind Hybrid System.

Table 1: Solar PV Panel Specifications (ENARAH ESPMC040).

Parameter	Value
Model	ENARAH ESPMC040
Rated Power (Pmax)	40 W
Vmp (Max Power Voltage)	18.3 V
Imp (Max Power Current)	2.19 A
Isc (Short-Circuit Current)	2.32 A
Voc (Open-Circuit Voltage)	22.7 V
Dimensions (mm)	415 × 674 × 25
Operating Temperature Range	−40 °C to +85 °C
Standard Test Conditions	AM1.5; 1,000 W/m²; 25 °C

PWM Solar Charge Controller

A 20A / 12–24 V PWM charge controller went in instead of an MPPT unit. That decision isn't free: with the panel parameters used here, MPPT would in theory pull around 27.2% more power (≈40 W versus ≈31.5 W). Table 2 has the full controller specs. At this scale, though, simpler and cheaper was the right call—MPPT can wait for a version worth the extra cost.

Table 2: PWM Charge Controller Specifications

Parameter	Value
Type	Solar PWM Charge Controller
Rated System Voltage	12 V / 24 V
Rated Charging Current	20 A
Max PV Input Voltage	50 V
Max PV Input Power (12 V system)	260 W

Energy Storage Battery

The battery consisted of a CSP CSPES7-12 sealed VRLA (12 V, 7 Ah) with a standby charging voltage of 13.5–13.8 V and a cyclic voltage of 14.4–15.0 V. One of the first design issues was powering the Arduino from the main bus. This caused the controller to reset every time a relay was switched. The solution was to add a separate 3.7 V Li-ion cell with a Type-C charging circuit and a 5 V boost converter. This solution separated the microcontroller from the transients that occurred on the power rail. The full battery specifications are listed in Table 3.

Table 3: VRLA Battery Specifications (CSP CSPES7-12).

Parameter	Value
Nominal Voltage	12 V
Nominal Capacity	7 Ah
Type	VRLA Sealed Lead-Acid (Non-spillable)
Standby Charge Voltage	13.50–13.80 V
Cyclic Charge Voltage	14.40–15.00 V

Load

The PWM controller's load terminal was connected to a 12 V / 27 W automotive lamp (type 881-V 27W12) so that battery power fed the lamp, while the photovoltaic and wind resources were dedicated to charging. The RY_LOAD relay channel (digital output D25) switches the load and responds to remote commands issued through the MQTT mobile application.

Relay Switching Board

The four relay channels were routed to a J7 optocoupler-isolated relay module (5V, active low). The optocoupler stage ensured galvanic isolation between the 5V logic signals and the higher voltage power circuits, which is especially needed for switching inductive loads.

Measurement Sensors

For voltage measurement, B25 resistive-divider modules (0–25V) were used for the PV (22.7V open-circuit), wind (≈20V boosted), and battery (15V). For current measurement, ACS712 Hall effect sensors were used. The firmware removed the approximate 2.5V analog midpoint and added a noise threshold. Wind, PV, battery, and output current were routed to pins A0–A3, and the respective voltage measurements were routed to pins A4–A7.

Communication and Display Hardware

The ESP8266 (NodeMCU) communicates serially with the Arduino via hardware serial1, operating at 9,600 baud. The 20x4 I²C LCD and DS1307 RTC are on the I²C bus (SDA = D20, SCL = D21). The SD card is interfaced with SPI (MOSI = D51, MISO = D50, SCK = D52, CS = D53). A buzzer sounds when any source voltage drops below 3 V. In Figure 3, all power paths are annotated with bold arrows, while sensor signals are annotated with thin arrows to depict the three-tier monitoring system across the full scope of the system.

Software and control algorithm

Arduino Mega Firmware

The firmware runs on a 10-second timed loop. Each cycle reads eight analog channels (four voltages, four currents) plus the LDR and control-bus voltage, then passes every channel through a Kalman filter before any further processing happens. Relay states get checked against command flags arriving from the ESP8266, per-channel power is computed as P = V × I, and the results land on the SD card as a time-stamped CSV row. The LCD advances to the next of its five rotating display pages, and the loop closes out with an alarm.

Electrical Interlock Logic

The interlock has no fallback — it cannot be compromised. Activating RY_PV immediately forces RY_W open, not just in firmware but at the hardware level too, through interlocked relay coil wiring. The PWM controller's PV input terminal physically cannot accept simultaneous injections from both sources. If both are commanded ON at once, PV wins, and wind waits.

ESP8266 Firmware and MQTT Architecture

The ESP8266 connects to test.mosquitto.org on port 1883 and publishes sensor readings roughly every 250 ms. It subscribes to the command topic STaJoRa_SWE25, translates incoming relay ON/OFF commands into serial flags, and passes them to the Arduino over Serial1. A reconnection routine handles Wi-Fi drops without any manual intervention.

Mobile Application

Built in MIT App Inventor, the mobile app connects to the same broker and shows four measurement pages: battery, output, wind, and PV, each with live voltage, current, power, and relay status. The manual relay buttons send MQTT commands straight to the ESP8266, so load switching and source control can happen from a phone anywhere there's an internet connection.

Data Logging and Protection Features

Each CSV row carries 17 fields: Voltage_Wind, Voltage_Solar, Voltage_Battery, Voltage_Output, Current_Wind, Current_Solar, Current_Battery, Current_Output, Relay_Wind, Relay_Solar, Relay_Battery, Relay_Output, DC_Circuit_Voltage, LDR_Value, Date, Time, and Day logged every 10 seconds with headers written once at file initialization. Protection comes from a line fuse on the battery feed, a forward-biased diode at the PV input to block reverse current, and filter capacitors on the battery bus to suppress relay-switching ripple. The optocoupler-isolated relay drivers, covered in Section II, do double duty here by keeping high-voltage transients off the logic rail. Figure 4 shows the theoretical PWM-versus-MPPT comparison for the 40 W panel and 12 V battery, with I–V and P–V curves marked at both the MPP and PWM operating point

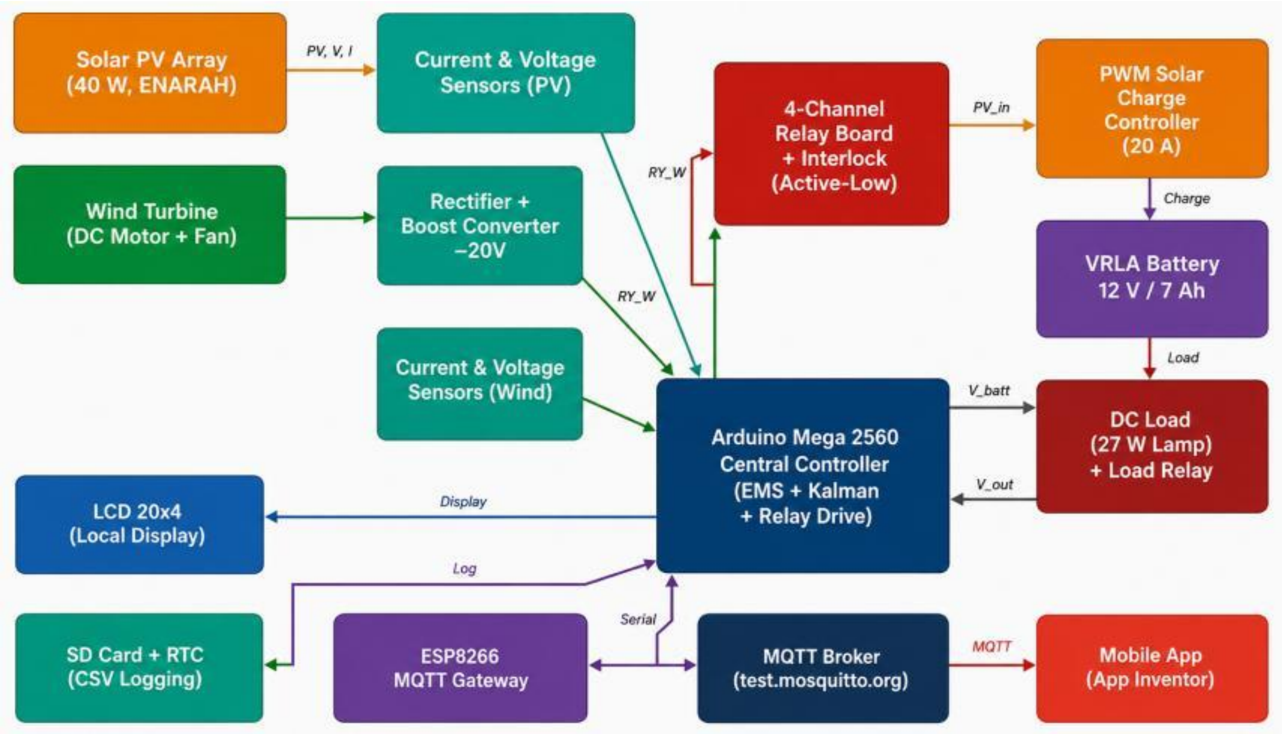

Figure 3: Custom Functional Architecture Block Diagram of the Smart Hybrid HRES

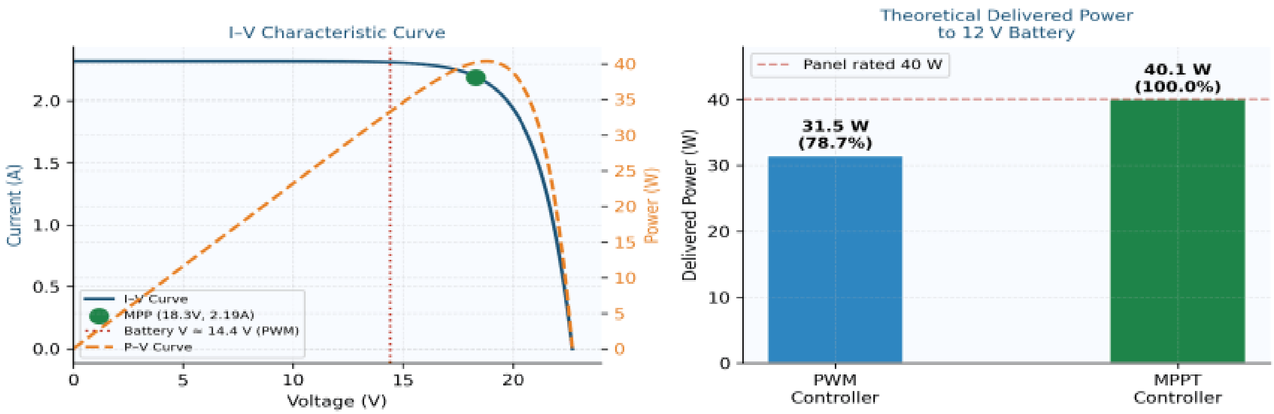

Figure 4: Theoretical Comparison of PWM and MPPT Performance for the 40 W Panel / 12 V Battery System

Mathematical modeling

The model captures both the steady-state and dynamic behavior of a DC-coupled HRES across four subsystem domains: energy conversion, power electronics, energy storage, and digital signal acquisition. The hardware set is a 40 W monocrystalline PV array; a wind channel emulated by a 24 V DC motor-fan assembly with full-bridge rectification and boost conversion; a 12 V / 7 Ah VRLA battery; and a PWM charge controller sitting under an MQTT-based IoT layer. The formulation was built to serve three implementation contexts at once — MATLAB/Simulink simulation, discrete-time embedded deployment on an Arduino Mega 2560, and control system design. The instantaneous power balance of the HRES follows:

$$u\_PV\ P\_PV + u\_wind\ P\_wind + u\_bat\ P\_bat,dis = P\_load\ u\_load + P\_bat,ch\ u\_ch + P\_loss \quad (1)$$

Where u_PV, u_wind, u_bat, and u_load ∈ {0, 1} are binary relay state variables; P_bat, dis, and P_bat, ch are the battery discharge and charge powers, respectively; and P_loss is the total system power loss. These variables are subject to the electrical interlock constraint:

$$u\_PV + u\_wind \leq 1 \quad (2)$$

The solar-source priority is hardcoded in the firmware: u_PV = 1 forces u_wind = 0 regardless of the remote command state. Net battery power is:

$$P\_bat,net = V\_bat \cdot I\_bat = P\_bat,dis\ (u\_bat, SOC) - P\_bat,ch\ (u\_ch, V\_bat) \quad (3)$$

System losses can be divided into four components: relay contact conduction, diode forward-drop, converter switching, and wiring ohmic losses [178,179].

$$P\_loss = I^2\_relay\, R\_relay + V\_f\, I\_diode + P\_sw + I^2\_line\, R\_line \quad (4)$$

Summing over N samples at T_s = 10 s provides the session energy balance:

$$E\_PV + E\_wind + E\_bat,dis = E\_load + E\_bat,ch + E\_loss \sum_i (u\_PV[k]\, P\_PV[k] + u\_wind[k]\, P\_wind[k])\, T\_s + \sum_i P\_bat,dis[k]\, T\_s = \sum_i P\_load[k]\, T\_s + \sum_i P\_bat,ch[k]\, T\_s + \sum_i P\_loss[k]\, T\_s \quad (5)$$

This formulation advances existing HRES models in one specific way: relay-state-integrated power balance. Equations (1) and (5) embed the electrical interlock constraint directly into the energy-flow equations through binary relay-state variables, rather than treating the interlock as a separate control rule layered on top — which is how prior HRES models tend to handle it. Folding the constraint into the equations themselves makes formal safety verification tractable through switched-system stability analysis and lets supervisory control laws be derived with constraint satisfaction already built in.

The solar irradiance is generated from measured data according to local studies [180-184]. Also, it is worth mentioning that the solar irradiance incident on solar field is different from that incident on a single panel or that recorded in the metrological stations [185-190].

Results and discussion

Experimental Setup and Test Sessions

All experiments were conducted at the College of Renewable Energy, Tajoura, across two sessions. Session B (16 January 2026, 27.5 minutes, 166 samples) confirmed that the core system — timestamped logging, relay switching, LCD display — was working correctly. It also caught a measurement fault: the ACS712 sensors on the wind-current and output-current channels read zero for the entire session, even with their respective relays active and confirmed closed. The fault traced back to the sensors themselves, which were faulty. Table 4 summarizes both sessions. Both sensors were replaced and recalibrated before Session C (13 March 2026, 31.0 minutes, 187 samples).

Session C Scenario Timeline

Session C was designed to test each operational mode on its own before combining them. The session stepped through defined stages in sequence — solar only, wind only, combined, load on, load off — so that each switching event could be judged independently. Figure 5 plots the full timeline; Table 5 maps every switching event to its stage and the observation it was meant to test.

Load-Stage Performance Analysis

Table 6 compares the three active load-feeding stages in Session C, and Figure 6 shows how output voltage, load current, and load power shifted across them. The combined-source stage is the baseline that matters most for judging overall system performance.

Table 4: Summary of Experimental Test Sessions.

Session	Date	Duration (min)	Samples	Time Range	Purpose
B	16 Jan 2026	27.5	166	04:33–05:01	Initial validation; sensor fault identification
C	13 Mar 2026	31.0	187	14:47–15:18	Post-correction definitive evaluation

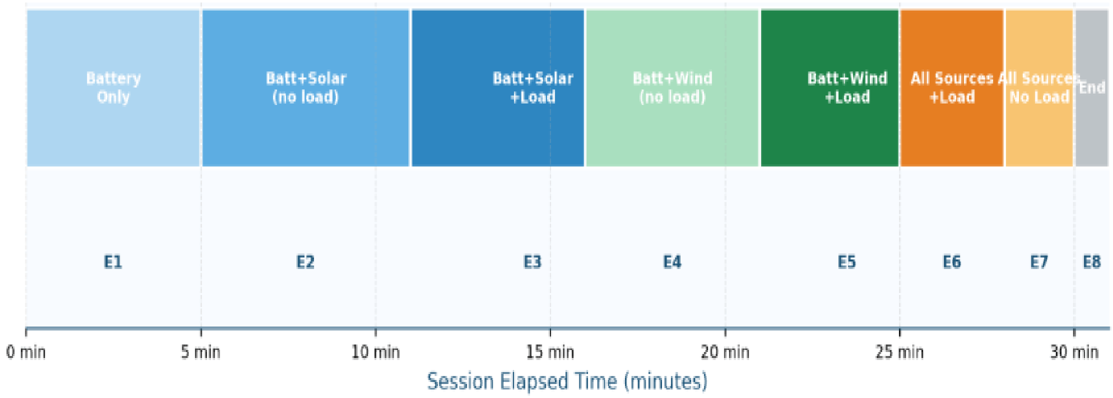

Figure 5: Session C Operational Stage Timeline

Table 5: Session C Event Timeline

Event	Time	Action	Resulting Stage	Analytical Note
E1	14:47	Battery relay ON	Battery only	Session start; baseline established
E2	14:52	Solar relay ON	Battery + Solar (no load)	Output voltage rises; quasi-no-load state
E3	14:58	Load relay ON	Battery + Solar + Load	Output voltage drops; load current appears
E4	15:03	Solar OFF; Wind relay ON	Battery + Wind (no load)	Wind contribution verified without load
E5	15:08	Load relay ON	Battery + Wind + Load	Weakest load-support stage of the session
E6	15:13	Solar relay ON (all sources)	All Sources + Load	Best output quality; solar recharges battery
E7	15:16	Load relay OFF	All sources, no load	Output voltage rises; load current drops to zero
E8	15:18	Wind relay OFF; session end	Session terminated	Final system checkout

Table 6: Comparative Load-Stage Performance — Session C.

Operating Stage	Duration (min)	Vout,avg (V)	Iload,avg; (A)	Pload,avg; (W)	Source Contributions
Battery + Solar + Load	5.00	13.00	1.82	23.62	Battery 5.1 W | Solar 33.9 W | Wind 0.0 W
Battery + Wind + Load	4.83	9.81	1.51	15.27	Battery 15.1 W | Solar 0.0 W | Wind 4.2 W
All Sources + Load	2.83	13.66	1.87	25.70	Battery 3.4 W | Solar 19.7 W | Wind 9.9 W

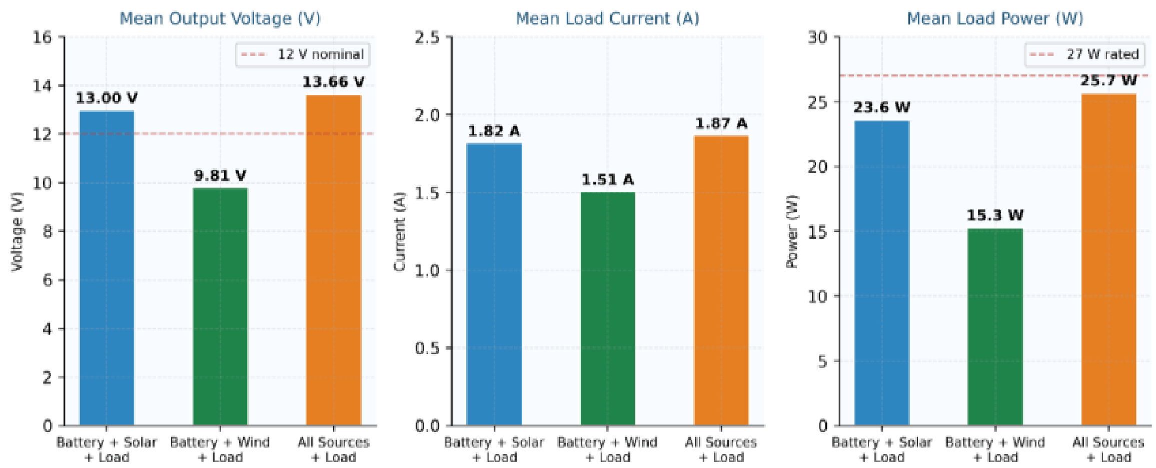

Figure 6: Comparative Load-Stage Performance — Session C

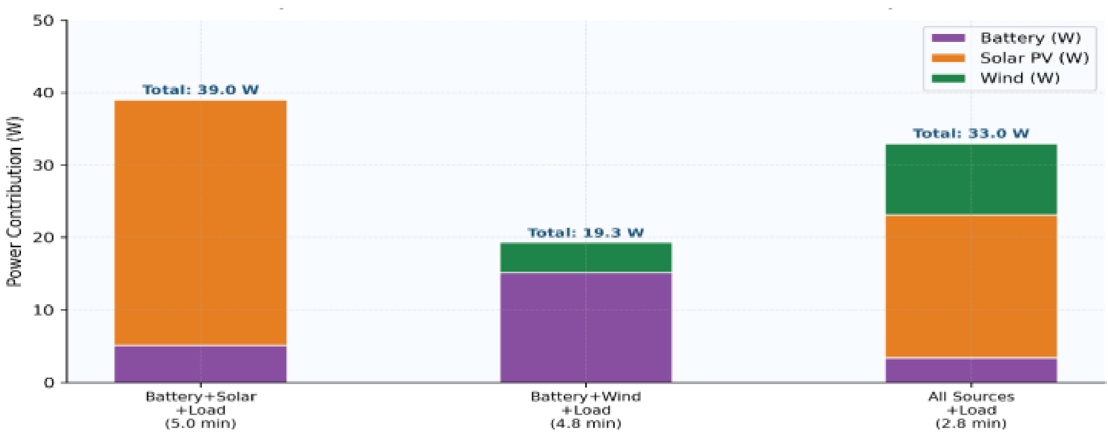

Figure 7: Stacked Bar Chart of Source Power Contributions per Active Load Stage — Session C

The all-sources stage produced the strongest result: mean load power of 25.70 W, peaking at 26.79 W — 99.2% of the 27 W rated load. Battery + Solar + Load came in lower, at 23.62 W. Battery + Wind + Load managed only 15.27 W, which is low but expected — the wind channel in this setup was a manually rotated motor simulator, not a turbine under sustained airflow. The spread across the three stages is the clearest evidence that source combination matters: solar alone gets close, wind alone falls well short, and together they land within 0.8% of rated load. Figure 7 adds the source-level picture, with PV and wind contributions stacked per stage so the relative weight of each source is visible at a glance.

Solar PV Channel Performance

Table 7 covers solar performance indicators for both sessions; Figure 8 plots the same data. Open-circuit voltage held steady across sessions 21.72 V in Session B, 21.70 V in Session C, against a nominal 22.7 V, close enough to confirm the voltage measurement path was working correctly in both runs. During active charging in Session B (samples where I > 0.05 A), mean panel voltage dropped to 13.90 V, which is exactly what you'd expect when a PWM controller clamps the panel to battery terminal voltage instead of tracking the maximum power point. Session C pushed higher: maximum recorded solar power was 34.36 W, 85.9% of the 40 W rated figure, with a peak current of 2.51 A. The 25.2% active-current sample ratio isn't a sign of weak solar performance; it just reflects that Session C cycled through multiple switching stages, several with the solar relay deliberately off.

Wind Channel Validation and Sensor Correction

Table 8 and Figure 9 compare the wind current channel before and after sensor replacement. The Session B picture was instructive: wind-channel voltage averaged 20.71 V through the rectifier and boost converter, both clearly working, yet the current channel read zero for every sample in the session. That combination, healthy voltage paired with a flat current trace, pointed to the sensor rather than anything upstream. After replacement and recalibration, Session C recorded a maximum wind current of 0.496 A and a peak wind power of 10.05 W. Every single sample where Relay Wind = 1 returned a non-zero current value. The control logic and circuit topology were never the problem; it was the sensor all along.

Table 7: Solar PV Channel Performance Indicators

Session	Voc, max (V)	I_{PV}, max (A)	P_{PV}, max (W)	V_{PV},avg at I>0.05A (V)	I_{PV},avg at I>0.05A (A)	Active-I Samples (%)
B	21.72	1.20	17.06	13.90	0.80	69.9%
C	21.70	2.51	34.36	13.22	2.06	25.2%

Table 8: Wind Current Channel Before and After Sensor Correction.

Condition	I_{wind}, max (A)	Non-Zero I Samples	Relay=1 with I>0 (%)	P_{wind}, max; (W)	Observation
Before correction (Session B)	0.00	0	0.0%	0.00	Sensor fault confirmed
After correction (Session C)	0.496	89	100%	10.05	Sensor validated

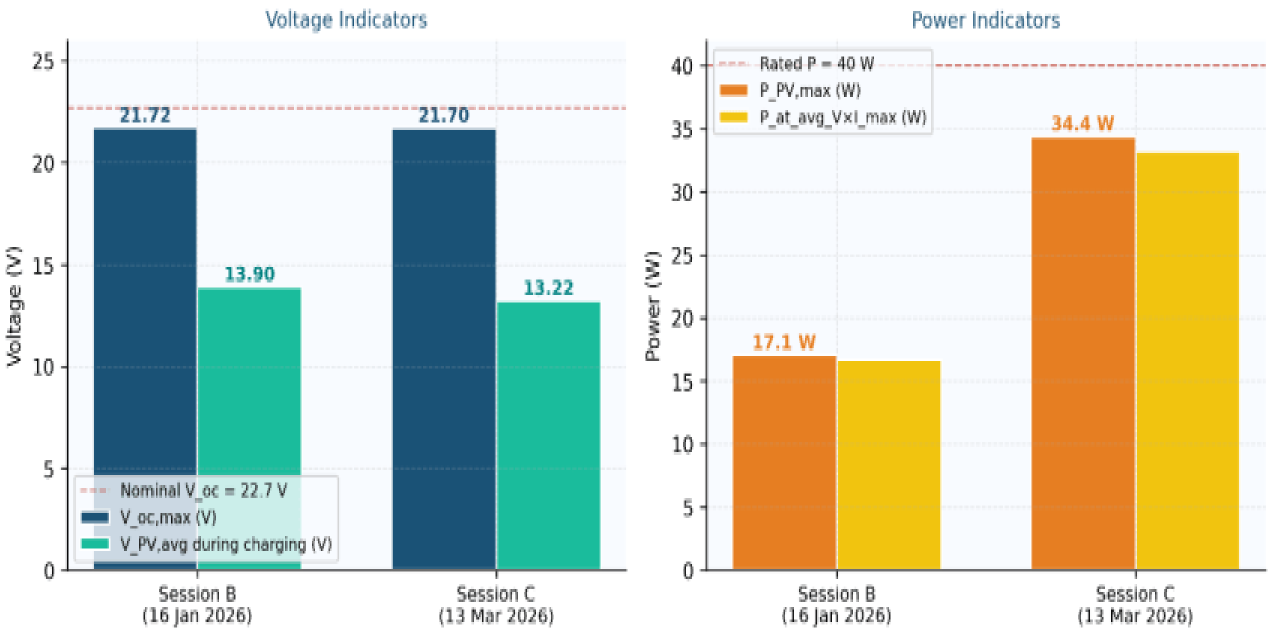

Figure 8: Solar PV Channel Performance Indicators Sessions B and C

Figure 9: Wind Current Channel Validation — Before and After Sensor Correction

Output Channel Validation

Table 9 and Figure 10 show the output current channel before and after sensor replacement. Session C recorded a maximum output current of 1.95 A, with 79 non-zero samples and 100% relay-measurement consistency — the same clean result as the wind channel. The more telling number is peak output power: 26.79 W, within 1.8% of the 27 W rated load. At that margin, the measurement isn't just plausible — it's close enough to call the load path verified.

Statistical Analysis of Key Channels

Descriptive statistics for the dominant electrical channels in Session C are presented in Table 10 and Figure 11. Across the channels is the pattern you would expect: Voltage channels are more stable than current and power channels. The output voltage is the most stable of all with a CV of only 17.4 %. Current and power readings are passed through to the battery bus to pick up fluctuations. The high dispersion of the solar and wind power channels (CV ≈ 110–126%) is not a measurement problem, but rather a consequence of the fact that the relays were turned on and off during the session as part of the test protocol. Remove the off-samples and the spread goes away. Two channels acted as near constants (the LDR (CV=0.6%), confirming the steady state of the outdoor irradiance during the whole of Session C, and the control-circuit voltage that kept exactly 5.0 V during both sessions. The isolated microcontroller supply did its job.

Table 9: Output Current Channel — Before and After Sensor Correction

Condition	I_{out}, max (A)	Non-Zero I Samples	Relay=1 with I>0 (%)	P_{out}, max (W)	Observation
Before correction (Session B)	0.00	0	0.0%	0.00	Sensor fault confirmed
After correction (Session C)	1.95	79	100%	26.79	Sensor validated

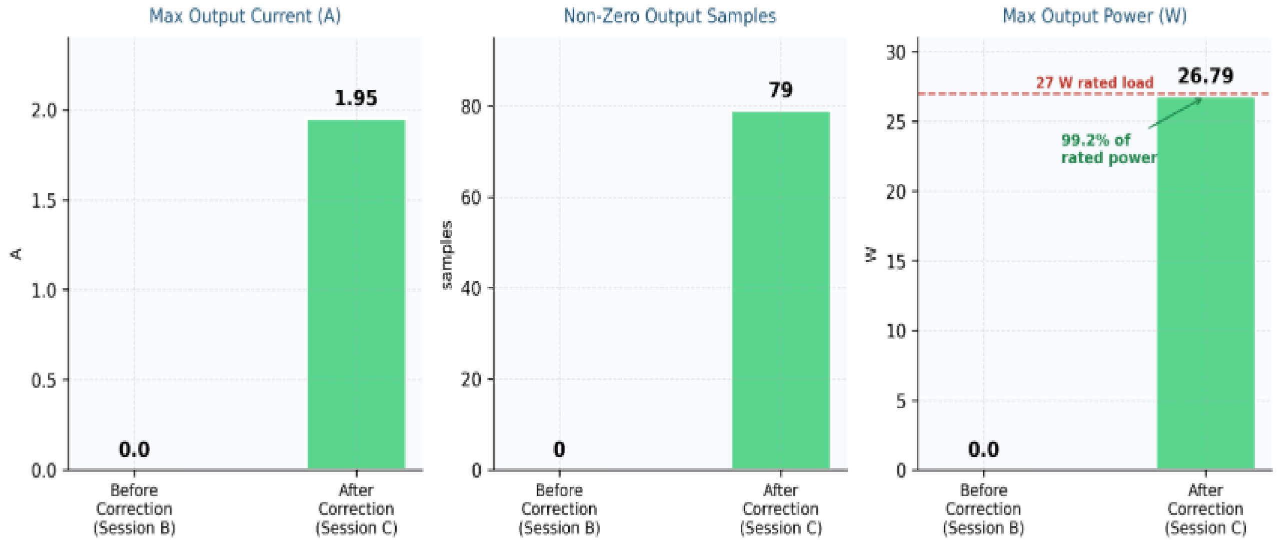

Figure 10: Output Current Channel Validation — Before and After Sensor Correction

Table 10: Descriptive Statistics for Main Channels — Session C

Channel / Variable	Unit	Mean	Std Dev	CV (%)	Interpretation
Voltage Solar	V	16.81	3.75	22.3	Affected by relay switching and charge state
Current Solar	A	1.01	1.11	109.9	High CV due to zero-current periods between activations
Power Solar	W	13.36	14.81	110.8	Reflects irradiance changes and switching cycles
Voltage Wind	V	6.49	7.66	118.1	Manual rotation transients and conditioning phase
Current Wind	A	0.22	0.23	106.0	High CV; wind inactive during several stages
Power Wind	W	2.95	3.54	120.2	Limited and variable wind contribution
Voltage Battery	V	11.99	2.96	24.7	Reflects charge/discharge balance
Current Battery	A	0.69	0.73	106.0	Varies with source and load transitions
Voltage Output	V	12.69	2.21	17.4	Lowest CV; battery bus buffering evident
Current Output	A	0.72	0.87	119.0	Directly linked to the load relay activation state
Power Output	W	8.84	11.09	125.5	Overall load performance indicator
LDR Value	%	98.18	0.59	0.6	Stable qualitative irradiance indicator

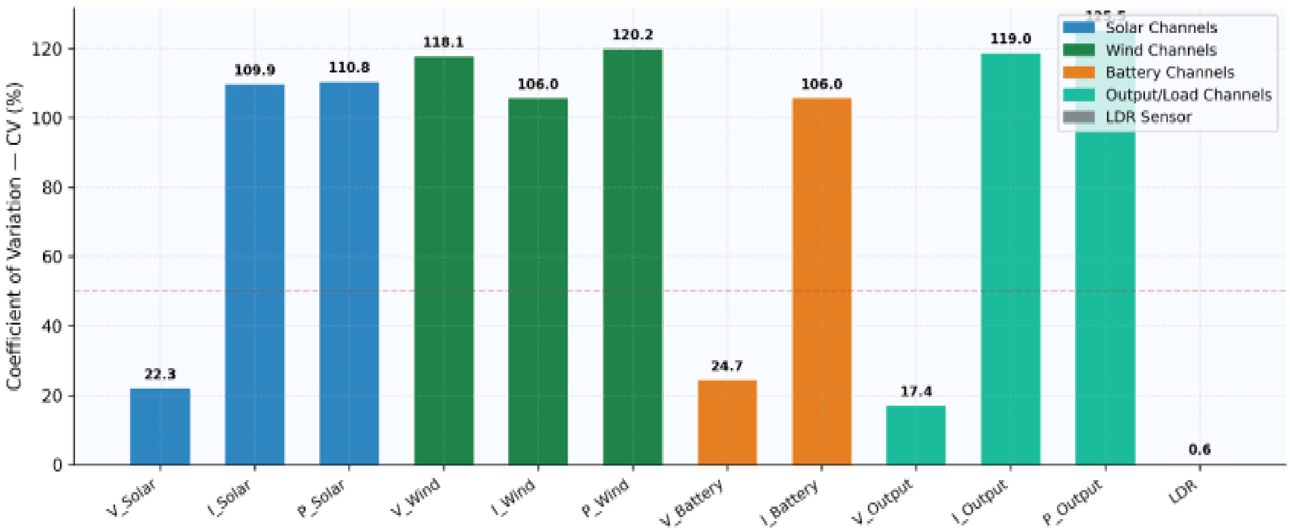

Figure 11: Coefficient of Variation (CV %) for Main Measurement Channels — Session C

Relay Logic Validation

Relay operating ratios are compared in both sessions in Table 11 and Figure 12. The difference is simple: Session B was mainly a solar-channel test, so RY_PV was active 94.6% of the time, and the other channels were not used much. Session C simply ran through every source and load configuration sequentially. The number that matters from Session C is the relay-current alignment: for both the wind and output channels, every sample with the relay active returned a non-zero current reading. “No exceptions. That result closes the loop on the sensor swap-out. The control logic was fine all along, and when the sensors worked, the measurements came through.

Discussion of Limitations

Four limitations restrict what we can and cannot learn from these findings. The wind source was a DC motor with fan.

Table 11: Relay Operating Ratios by Session

Relay Channel	Session B (%)	Session C (%)	Notes
RY_W (Wind)	39.2	24.4	Lower in Session C due to multi-scenario switching
RY_PV (Solar)	94.6	27.1	Session B was a dedicated solar-channel validation session.
RY_BAT (Battery)	87.3	52.1	Active for the majority of both sessions
RY_LOAD (Output)	62.0	21.6	Load activated only during specific test stages

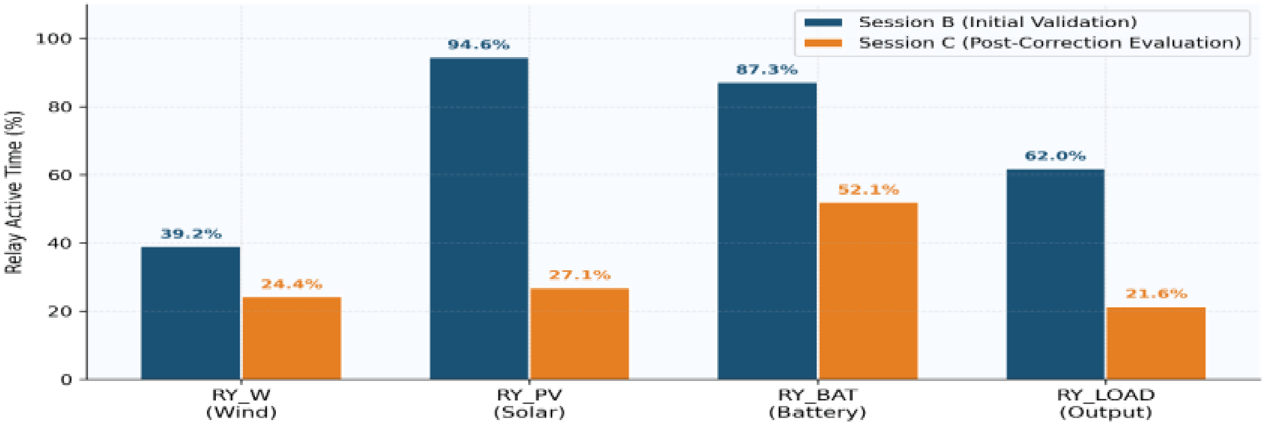

Figure 12: Relay Operating Ratios for Sessions B and C

blades attached to the shaft and turned by hand during testing. The power numbers from that channel tell you the circuit works: rectifier, boost converter, relay, measurement, but not how the system would behave with a real turbine in sustained wind. We haven't done the test yet. The PWM charge controller is a conscious cost compromise: an MPPT unit would in theory recover about 27% more solar power under the same conditions (see Figure 4). PWM was the right call at prototype scale, probably not at field scale. The MQTT setup uses a public broker, which is fine for a lab demonstration but not for anything operational. The command topic is neither encrypted nor authenticated. Anyone who knows the topic string can issue relay commands. That has to be changed before the system goes out into the lab." Finally, source switching is manual: the relay logic performs commands but does not decide when to switch based on what the sources are actually producing. The most important remaining improvement to implement is an automatic EMS mode that reads real-time voltage and current and switches accordingly.

CONCLUSIONS

Wind-turbine performance data is marked with an asterisk. The experimental source was made up of a DC motor with fan blades mounted on its rotor, manually operated. This is adequate to test the integrity of the rectifier, boost converter, relay, and measurement system. But this setup lacks details that can be obtained from the performance of the system when connected to a real turbine under continuous airflow. The PWM controller was chosen because of its affordability. It fails to track the maximum power point of the panel, and this is shown in Figure 4 through figures; an MPPT would gain about 27% more PV energy. Though this tradeoff is understandable in a prototype setup, it is highly unlikely in a field deployment. The most restrictive component of the system is the MQTT layer. A public broker with an unencrypted and unauthenticated command topic was used. As such, remote relay commands could be sent by any individual who knows the topic. This is fine in a laboratory environment of a college but not elsewhere. Switching of sources still requires manual intervention. The relay logic gives commands, which are implemented properly. But the existing firmware cannot make decisions on what actions to take for switching based on the outputs of the sources. Introduction of a decision-making level in the form of an EMS, which reads live current and voltage and acts accordingly, would change the prototype to a self-managing system.

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