

Article

Experimental Validation and Load-Supply Feasibility Assessment of a Battery-Coupled Wind–Photovoltaic Auxiliary Power System for a Small Marine Vessel

Ciprian Popa ¹ , Florențiu Deliu ^{1,*} , Iancu Ciocioi ¹ , Andrei Darius Deliu ², Petrică Popov ¹,
Adelina Rodica Bordianu ² , Adrian Popa ¹ , Narcis Octavian Volintiru ¹ , Doru Coșofreț ¹ 
and Gheorghe Samoilescu ¹

¹ Faculty of Marine Engineering, Romanian Naval Academy “Mircea cel Bătrân”, 900218 Constanța, Romania; ciprian.popa@anmb.ro (C.P.); iancu.ciocioi@anmb.ro (I.C.); petrica.popov@anmb.ro (P.P.); adrian.popa@anmb.ro (A.P.); octavian.volintiru@anmb.ro (N.O.V.); doru.cosofret@anmb.ro (D.C.); gheorghe.samoilescu@anmb.ro (G.S.)

² Faculty of Electrical Engineering, National University of Science and Technology Politehnica, 060042 Bucharest, Romania; andrei_darius.deliu@stud.electro.upb.ro (A.D.D.); adelina.bordianu@upb.ro (A.R.B.)

* Correspondence: florentiu.deliu@anmb.ro

Abstract

This study develops and experimentally validates a battery-coupled wind–photovoltaic power model for auxiliary electrical supply in small-vessel systems. The prototype integrates a 395 W CS6R-395MS monocrystalline photovoltaic module (CSI Solar Co., Ltd., Suzhou, Jiangsu, China), a 200 W FA200W horizontal-axis wind turbine (VEVOR, Rancho Cucamonga, CA, USA), maximum power point tracking (MPPT) power-conditioning stages, a 24 V/28 Ah AGM VRLA battery bank composed of four BAT212120086 batteries (Victron Energy B.V., Almere, The Netherlands), a 24 V DC bus, and a Phoenix 24/500 pure sine-wave inverter (Victron Energy B.V., Almere, The Netherlands), targeting non-propulsion navigation, communication, and lighting loads on a 5.7 m length overall (LOA) vessel. Field-acquired irradiance, cell temperature, incidence angle, PV voltage, wind speed, and rotor-speed data were used as time-dependent model inputs and compared with synchronized active-power measurements. Across the full 15–24 September 2025 experimental campaign, the maximum absolute relative error remained below 2.69%, while the aggregate statistical validation indices were ME = −0.1041 W, MAE = 0.3988 W, RMSE = 0.4931 W, and MAPE = 0.5946%. For the representative cloud-adverse case study conducted on 21 September 2025, the measured hybrid generation reached $E_{\text{hyb}} = 611.3$ Wh over 8.28 h, corresponding to $C_{\text{RES}} = 102.1\%$ of the selected $E_{\text{load}} = 599$ Wh/day auxiliary-load profile and to $C_{\text{hyb+bat}} = 158.1\%$ when the usable battery reserve at 50% depth of discharge (DOD) was included.



Academic Editor: Decheng Wan

Received: 6 July 2026

Revised: 24 July 2026

Accepted: 2 August 2026

Published: 4 August 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

Keywords: auxiliary electrical supply; battery energy balance; DC bus; experimental validation; hybrid renewable energy system; photovoltaic module; renewable energy; small marine vessel; wind turbine

1. Introduction

Public concern about environmental sustainability has intensified, particularly in relation to the steady increase in atmospheric carbon dioxide, widely identified as a key contributor to climate change [1–4]. Meeting modern societal energy needs relies on primary

resources that are commonly grouped into two broad classes: non-renewable sources (e.g., coal, petroleum, natural gas, and uranium) and renewable sources (e.g., hydropower, wind, marine energy, geothermal energy, solar energy, and biomass) [5–7]. Given the limited buffering capacity of natural ecosystems and the accelerating environmental deterioration associated with large-scale fossil-fuel utilization, there is a clear need for technological solutions that both lower ecological footprints and strengthen the robustness of electricity provision [8,9]. This requirement becomes especially pressing during high-impact events, such as natural disasters, extreme weather, or widespread infrastructure failures, when conventional power systems can be disrupted, constrained, or altogether unavailable.

The IMO regulatory framework includes the Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII), while the 2023 IMO GHG Strategy targets net-zero GHG emissions from international shipping by or around 2050 and promotes the uptake of zero- and near-zero-GHG technologies, fuels, and energy sources. At European level, FuelEU Maritime has applied from 1 January 2025 and requires progressive reductions in the GHG intensity of energy used on board ships calling at EU ports. Within this context, small-scale hybrid WT–PV auxiliary systems are not a substitute for ship-wide decarbonization measures, but they provide a practical experimental pathway for reducing auxiliary electrical demand supplied by conventional fuel-based sources [10–14].

Maritime transport is currently undergoing a significant technological transition driven by increasingly stringent requirements for decarbonization, energy efficiency, and reduction of greenhouse gas emissions [10–14]. Although large commercial vessels remain the main focus of international regulatory frameworks, small marine vessels also represent an important category of energy consumers, particularly in coastal operations, training activities, short-distance navigation, fishing, research missions, and auxiliary maritime services. In these applications, the electrical demand associated with onboard auxiliary consumers, such as navigation equipment, communication systems, lighting circuits, monitoring devices, control units, bilge pumps, ventilation systems, and low-power service loads, is commonly supplied by conventional fuel-based generation systems. This dependence on fossil fuels increases operational costs, contributes to local emissions, and reduces the energy autonomy of the vessel, especially during prolonged missions or operation in areas where fuel supply is limited.

In this context, the integration of renewable energy sources on board small marine vessels has become a technically relevant solution for reducing fuel consumption and improving onboard energy sustainability. Photovoltaic and wind energy systems are particularly suitable for maritime applications because they can exploit naturally available environmental resources without requiring continuous fuel supply. Solar radiation can be converted into electrical energy through photovoltaic modules installed on available deck surfaces, while wind energy can be harvested using compact wind turbines adapted to the aerodynamic and spatial constraints of marine platforms. However, the implementation of renewable-energy systems on board vessels is more complex than in stationary land-based applications, because the energy conversion process is strongly influenced by variable environmental conditions, vessel motion, shading effects, wind turbulence, saltwater exposure, limited installation space, and fluctuating load profiles [15–19].

A major technical challenge associated with onboard renewable-energy generation is the intermittent and partially unpredictable character of the available energy resources [8]. Solar irradiance varies according to the time of day, season, atmospheric conditions, cloud coverage, and the relative orientation of the photovoltaic panels. Similarly, wind speed and wind direction are affected by local meteorological conditions [20], vessel heading, apparent wind components, and the dynamic interaction between the marine environment and the vessel superstructure. As a result, the instantaneous power output of a single

renewable energy source may not correspond to the real-time demand of the onboard consumers. This mismatch can lead to periods of insufficient generation, excess energy production, reduced utilization efficiency, or increased stress on the energy storage system.

For this reason, hybrid renewable-energy systems based on the combined use of photovoltaic and wind sources represent a more robust solution [21,22] for small marine vessels than configurations relying on a single renewable source. The complementarity between solar and wind resources can improve the continuity of power generation [23], since reduced photovoltaic production may be partially compensated by wind energy availability, particularly during cloudy periods, night-time operation, or specific seasonal conditions. Conversely, solar energy can contribute significantly during periods of low wind speed and high irradiance. This complementary operating behavior can reduce the variability of the total generated power, improve the reliability [22,24,25] of the onboard electrical supply, and decrease the dependence on conventional auxiliary generators [26].

In isolated marine applications, where the onboard power system operates independently from the utility grid, the hybrid energy system must ensure the balance between generation, storage, and consumption under variable operating conditions. Unlike grid-connected systems, autonomous onboard configurations cannot export surplus energy to an external network or import power during renewable generation deficits. Therefore, the system architecture must include appropriate energy storage, power electronic interfaces, control strategies, and energy management algorithms capable of maintaining voltage stability, regulating power flow, protecting the components, and ensuring the continuous supply of critical loads. The correct sizing and coordination of these elements are essential for achieving a reliable and efficient autonomous energy system [27]. The general topology of a small-scale autonomous hybrid renewable-energy system is illustrated in Figure 1.

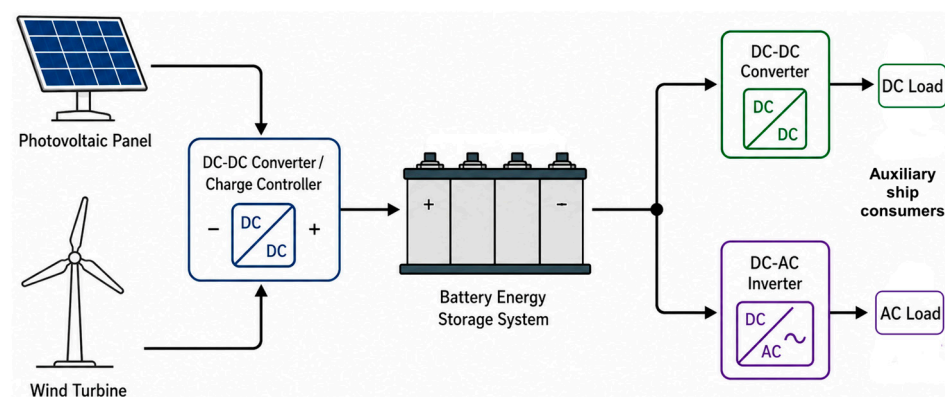


Figure 1. Small-scale autonomous hybrid renewable-energy system.

The performance of a hybrid wind–photovoltaic system installed on a small marine vessel depends on several design and operational parameters, including the annual energy demand of the onboard consumers, the available solar irradiance, the wind speed distribution, the rated power of the renewable sources, the battery capacity, and the efficiency of the power conversion stages. In addition, the dynamic behavior of the system can be improved by using maximum power point tracking algorithms for the photovoltaic subsystem and appropriate control methods for the wind-energy conversion subsystem. As a result, maintaining dependable delivery typically requires a combination of robust supervisory control, adaptive station-keeping/positioning strategies, and appropriately sized energy storage to smooth short-term variations and support continuity of supply [28,29]. These control strategies allow the system to extract the maximum available power from the renewable sources while adapting to rapid changes in meteorological and loading conditions.

Considering these aspects, the development of a hybrid renewable-energy system for small marine vessels requires an integrated approach that combines resource assessment, mathematical modelling, simulation, experimental validation, and energy management analysis. Such an approach makes it possible to evaluate the technical feasibility of the proposed architecture, estimate the contribution of each renewable source, determine the energy autonomy of the vessel, and quantify the potential reduction in fuel consumption for auxiliary onboard loads. Therefore, the present study focuses on the analysis and development of a wind–photovoltaic hybrid system intended to supply selected auxiliary consumers of a small marine vessel, with the objective of improving onboard energy autonomy, increasing the utilization of renewable resources, and supporting the transition toward more sustainable maritime energy solutions.

The novelty of this study does not lie in the individual use of photovoltaic panels, wind turbines, batteries, or MPPT controllers, which are well-established technologies, but in the experimental validation of an integrated battery-coupled WT-PV auxiliary power system under a small-vessel application scenario. The contribution is the combined treatment of: (i) a real low-power marine auxiliary supply architecture, (ii) synchronized field measurements of PV, wind, battery, and load-related variables, (iii) comparison between simulated and measured hybrid power, and (iv) an energy-feasibility assessment against representative auxiliary loads of a 5.7 m vessel.

2. Maritime Application Framework

2.1. Type of Maritime Application

The proposed hybrid renewable-energy system is intended for a small marine vessel with a length overall (LOA) of 5.7 m, operating with a low-voltage onboard electrical architecture. The system integrates a 200 W wind turbine and a 395 W photovoltaic module to support the auxiliary DC/AC power network. Its function is not related to propulsion, but to the partial supply of low-power onboard consumers and to battery charging during navigation, anchoring, harbour operation, or training activities.

2.2. Electrical Consumers

The hybrid system is designed to supply selected auxiliary consumers installed on a small vessel through a 24 V DC onboard distribution architecture. The renewable sources charge the battery bank via dedicated controllers, while the stored energy can be delivered directly to 24 V DC loads, such as navigation lights, interior lighting, GPS equipment, VHF radio, monitoring sensors, control circuits, battery monitoring devices, and other low-power DC consumers.

For equipment requiring alternating current, the system can also supply 230 V AC loads through a 24 V DC → 230 V AC inverter. In this configuration, the inverter acts as a power electronic interface between the DC battery bus and AC consumers, enabling the operation of selected low-power AC devices. Therefore, the hybrid system supports both direct DC supply and AC supply through conversion, with the inverter efficiency included in the overall energy balance when 230 V AC consumers are considered.

2.3. Load Profile

The electrical load profile is variable and depends on the vessel operating mode. During navigation, the demand increases due to the simultaneous operation of navigation, communication, lighting, monitoring, and safety-related equipment. During anchoring or harbour operation, the load is reduced, but essential consumers may remain active. Therefore, the load profile must be treated as a time-dependent demand, requir-

ing battery storage to compensate for the mismatch between renewable generation and instantaneous consumption.

2.4. Operating Conditions

The photovoltaic subsystem is influenced by solar irradiance, cell temperature, incidence angle, module orientation, partial shading, and reflected irradiance. The wind subsystem depends on wind speed, relative wind direction, turbine power curve, mechanical transmission losses, synchronous generator efficiency, and wind charge-controller efficiency. In maritime operation, both sources are affected by vessel motion, variable orientation, turbulence, and changing environmental conditions. Consequently, the useful output power must be evaluated after applying the conversion efficiencies of the main components.

2.5. Role of the Hybrid Renewable-Energy System

The role of the hybrid system is to increase the energy autonomy of the vessel by converting available solar and wind resources into useful electrical power for the auxiliary network and battery bank. The photovoltaic module provides energy mainly under favourable irradiance conditions, while the wind turbine can contribute when sufficient wind speed is available. The hybrid configuration improves generation continuity compared with a single-source system, reduces the load imposed on conventional auxiliary generation, and supports the onboard energy balance through renewable-based battery charging.

3. Design and Integration of a Functional Hybrid Wind–Photovoltaic Energy System Prototype

3.1. Critical Design Factors

In a hybrid architecture with two renewable energy sources connected to a common distribution bus, the total available electrical power is obtained by superimposing the power contributions of each subsystem, provided that electrical compatibility and coordinated control are ensured [30–33]. For DC-bus integration, voltage-level matching and dedicated power electronic interfaces are required. For AC coupling, phase, frequency, and voltage synchronization are mandatory.

The power contribution of the wind and photovoltaic subsystems is inherently variable, depending on wind speed and solar irradiance. Therefore, system stability requires an energy management strategy capable of regulating power flows between the generation units, storage system, distribution bus, and loads. This control layer must prevent overloads, circulating currents, voltage imbalance, and operation outside the admissible limits.

Consequently, the performance of the hybrid system is not determined only by the rated power of the sources, but also by electrical compatibility, conversion efficiency, control quality, and the ability to maintain stable operation under variable environmental conditions.

3.2. Design-Phase Issues

3.2.1. Energy Management System

During the initial design stage, both renewable sources were connected to the distribution bus through their respective controllers, while the battery bank was directly coupled to the same bus. This configuration produced voltage-level deviations and non-uniform voltage drops across the bus, which impaired the correct estimation of the battery voltage and state of charge by the charge controllers. As a result, the battery bank was not charged uniformly, leading to progressive energy imbalance over repeated operating cycles. Under higher AC loads supplied through the inverter, the reduced battery voltage triggered the inverter low-voltage alarm and disconnected the AC output.

To mitigate this issue, the battery bank was connected directly to the solar charge controller, which was used as the main energy management interface. The DC load output of the controller was then connected to the distribution bus. The wind subsystem remained connected to the bus through the wind-controller output, together with the inverter and data acquisition unit. Consequently, the hybrid system included both internal DC consumption, associated with the acquisition board, smart shunts and inverter standby operation, and external AC consumption supplied through the inverter.

3.2.2. Solar Charge Controller Ports

A second issue was identified during the experimental tests, related to the load port of the solar charge controller. The controller's battery protection algorithm dynamically adjusted the load-disconnection threshold to prevent battery degradation caused by repeated partial-charge cycles. When the available photovoltaic energy was insufficient for daily full recharge, this algorithm could interrupt the DC load output. To avoid unintended load disconnection, the controller was interfaced with the distribution bus through the battery output terminals instead of the dedicated DC load port. This modification required revision of the electrical schematic and ensured continuous load supply from the battery bank.

3.2.3. Incorrect Smart Shunt Connections

A third design issue concerned the wiring of the smart shunt measurement units. Although the shunt must be installed on the negative terminal of the monitored equipment, it also requires a positive supply reference for accurate data acquisition. Initially, the positive terminals of the shunts were connected to the distribution bus, causing erroneous measurements due to bus voltage-drop variations. The wiring scheme was therefore corrected by connecting the shunt supply directly to the positive terminal of the battery bank and to the positive output of the wind controller. This ensured reliable monitoring of the battery parameters and wind-controller output variables.

3.3. Experimental Architecture and Design of the Hybrid RES Prototype

3.3.1. Wind-Energy Conversion System (WECS) Topology, Rectification Stage

The experimental platform was developed to evaluate the performance of a low-power autonomous wind energy system designed to supply auxiliary electrical loads on a small vessel with an overall length of 5.7 m. The prototype integrates wind-energy conversion, power conditioning, electrochemical storage, DC–AC conversion, and electrical parameter acquisition within a unified experimental architecture.

The system is based on a 200 W FA200W (Table 1) (VEVOR, Rancho Cucamonga, CA, USA) horizontal-axis wind turbine coupled to an F100 maximum power point tracking wind charge controller (VEVOR, Rancho Cucamonga, CA, USA). The controller provides AC–DC rectification, charging regulation, overcharge protection, and stabilization of the energy transfer process. In this configuration, the controller operates as the main power conditioning interface, converting the variable electrical output of the turbine into a regulated DC flow suitable for direct distribution to DC auxiliary loads, and subsequent DC–AC conversion. The regulated output of the F100 MPPT wind controller was connected directly to the DC distribution bus, thereby enabling the supply of direct-current consumers while simultaneously providing the required energy interface for the inverter stage.

Table 1. Technical specifications of the hybrid system.

WECS FA200W		PV CS6R-395MS	
Parameter	Specifications	Parameter	Specifications
Type	Three-blade, upwind, 0° blade-pitch angle	Module technology	Monocrystalline
Power control	Fixed-pitch rotor	Rated power, P_{max}	395 W
Rated power	200 W	Maximum power voltage, V_{mp}	30.6 V
Rated voltage	24 V	Maximum power current, I_{mp}	12.91 A
Rotor diameter	1.2 m	Open-circuit voltage, V_{oc}	36.6 V
Cut-in wind speed	2.5 m/s	Short-circuit current, I_{sc}	13.77 A
Rated/optimal wind speed	12 m/s	Module efficiency	20.2%
Generator type	Permanent-magnet synchronous generator	Power tolerance	0 to +10 W
Generator efficiency	95%	Temperature coefficient of P_{max}	−0.34%/°C
		Temperature coefficient of V_{oc}	−0.26%/°C
		Temperature coefficient of I_{sc}	0.05%/°C

3.3.2. Photovoltaic Energy Conversion System (PV-ECS) Configuration

The photovoltaic subsystem was configured as an autonomous PV energy conversion branch integrated into the common storage and DC–AC conversion architecture of the hybrid prototype. It was implemented using a 395 W CS6R-395MS photovoltaic module (Table 1) (CSI Solar Co., Ltd., Suzhou, Jiangsu, China), selected to match the auxiliary-load demand and the charging requirements of the 24 V electrochemical storage subsystem.

The PV generator was coupled to the battery bus through a SmartSolar MPPT 75/15 charge controller, which acts as the PV-side power conditioning interface. By continuously adapting the operating point of the photovoltaic module to its maximum power point, the controller optimizes the conversion of solar irradiance into usable DC energy and regulates the charging process of the battery bank. The device also monitors the PV-side voltage and current and provides protection against overcharging, deep discharge, and non-permissible operating regimes.

From the battery bank, the regulated PV energy is injected into the 24 V DC bus, where it can supply direct-current consumers or be transferred to the downstream inverter stage. This configuration enables the photovoltaic subsystem to operate as a complementary renewable energy source within the hybrid RES prototype, supporting both battery replenishment and auxiliary-load supply under standalone operating conditions.

3.3.3. Architecture of the Hybrid Renewable-Energy System (RES) Prototype

The electrochemical storage subsystem was implemented by means of four 12 V, 14 Ah AGM VRLA batteries, model BAT212120086, interconnected in a combined series–parallel topology. Two batteries were first connected in series to obtain the required 24 V nominal DC level, while two identical series strings were subsequently paralleled to increase the available storage capacity (Figure 2). The resulting battery bank provided an equivalent configuration of 24 V and 28 Ah, ensuring sufficient short-term energy availability for the experimental validation tests. It should be noted that the storage capacity was not dimensioned according to a complete load-side energy balance intended to cover the entire auxiliary demand profile of the vessel. Instead, the battery bank was configured to provide an additional short-duration energy buffer and to enable autonomous operation of the prototype within the constraints imposed by the available experimental resources.

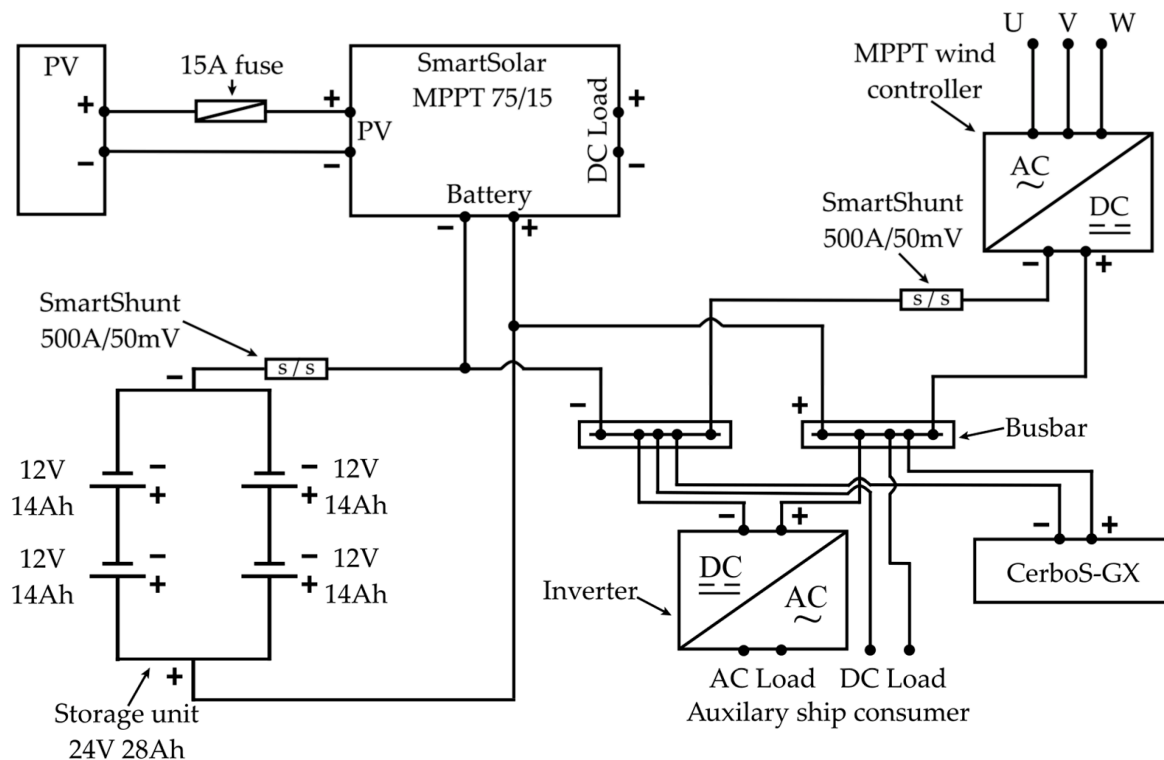


Figure 2. Electrical diagram of the hybrid RES prototype.

The battery bank was represented as an energy-buffering subsystem, with the allowable operating window constrained by a conservative depth-of-discharge criterion. In accordance with the manufacturer's technical specifications, a 50% depth of discharge (DOD) was adopted, corresponding to an expected lifetime of approximately 600 charge–discharge cycles under the specified operating conditions. This value was selected as a practical compromise between usable storage capacity and cycle-life preservation. Although operation at a lower discharge depth, such as 30% DOD, would theoretically extend the expected cycle life to approximately 1500 cycles, it would also substantially reduce the exploitable energy reserve available for the hybrid WT–PV system during experimental operation.

Therefore, the 50% DOD threshold was considered an appropriate trade-off for the present study, ensuring sufficient energy-buffering capability while maintaining a technically acceptable battery lifetime. A detailed electrochemical representation of the battery was beyond the scope of the present work. Consequently, second-order battery effects, including Peukert-related capacity variation, temperature-dependent capacity derating, charge-acceptance limitations, aging-induced degradation, internal-resistance evolution, and detailed state-of-charge uncertainty, were not explicitly modeled. These effects may become relevant for long-duration autonomy assessment, lifetime-oriented optimization, and extended maritime operating scenarios, and should therefore be incorporated in future experimental campaigns and advanced battery modeling studies.

For AC auxiliary loads, both the energy stored in the battery bank and the active DC power available on the distribution bus were supplied to a Phoenix 24/500 pure sine-wave inverter. This conversion stage enabled the transformation of the 24 V DC bus voltage into a 230 V AC output suitable for alternating-current onboard consumers. In this configuration, the inverter operates as the load-side power conditioning interface, decoupling the DC storage and generation architecture from the AC auxiliary load domain.

The electrical layout was designed to minimize parasitic resistive asymmetries within the low-voltage DC section. Therefore, the positive and negative DC conductors were routed with equivalent lengths, thereby reducing unequal voltage drops and current-

sharing deviations along the distribution paths. The same design constraint was applied to the interconnections between the battery strings, the DC busbar and the intelligent shunt-based measurement resistor, in order to improve measurement consistency, reduce conductor-related imbalance and preserve the accuracy of the experimental power-flow assessment.

From an energy management and distribution perspective, both renewable sources are coupled to a common DC bus through dedicated power electronic controllers. The F100 MPPT wind controller rectifies and regulates the output of the 200 W turbine FA200W, while the SmartSolar MPPT 75/15 charge controller manages the 395 W CS6R-395MS photovoltaic module and the battery-bank interface. Since the sources are integrated on the DC side, AC synchronization constraints related to phase, frequency, and voltage are eliminated.

The generated power is allocated according to the instantaneous load demand and the battery state of charge. When the combined renewable generation exceeds the load requirement, the surplus energy is transferred to the battery bank. Conversely, when the electrical demand is higher than the available renewable power, the deficit is supplied by the batteries. Minor current-sharing deviations may occur due to conductor resistance, contact resistance, and component voltage drops; however, these effects are limited by the regulation functions of the charge controllers and the DC bus topology.

3.4. DAQ-Based Monitoring and Experimental Instrumentation

Following the assembly, integration, and commissioning of the standalone photovoltaic experimental prototype, a dedicated outdoor monitoring campaign was conducted to obtain a time-synchronized dataset suitable for validating the Simulink (R2023a)-based photovoltaic wind model under real operating conditions. The electrical quantities associated with the photovoltaic subsystem were continuously recorded through the monitoring architecture, with one-minute temporal resolution. The acquired variables included the photovoltaic terminal voltage $V_{PV}(t)$, the photovoltaic output current $I_{PV}(t)$, and the corresponding instantaneous electrical power.

The present analysis focuses on the energy conversion performance of the photovoltaic subsystem and uses the experimentally measured time series as the reference dataset for evaluating the predictive capability of the mathematical model. Particular attention was given to both quasi-stationary operating intervals and irradiance-induced transient regimes, since these conditions are essential for assessing the robustness of the model under realistic environmental excitation.

The plane-of-array solar irradiance $S(t)$, corresponding to the tilted surface of the photovoltaic module, was measured at one-minute resolution using an ISO 9060:2018I [34] Class A pyranometer (Hukseflux, Delft, The Netherlands) connected to a CR1000X datalogger (Campbell Scientific, Logan, UT, USA). This acquisition chain ensured deterministic scan execution, consistent data logging, and timestamp alignment with the electrical measurement stream. The use of an ISO 9060 Class A radiometer provides a metrologically traceable irradiance input, since the standard imposes strict limits on key error sources, including response time, zero offsets, nonlinearity, directional response, spectral mismatch, temperature dependence, and tilt sensitivity.

For Class A pyranometers, ISO 9060 specifies restrictive performance limits, such as a 95% response time below 10 s, zero offset A within $\pm 7 \text{ W/m}^2$, nonlinearity within $\pm 0.5\%$, spectral error within $\pm 0.5\%$, and tilt response within $\pm 0.5\%$. These characteristics make the irradiance signal appropriate for time-domain validation of photovoltaic models subjected to clear-sky operation as well as moderate irradiance fluctuations caused by atmospheric variability.

The Campbell Scientific CR1000X datalogger was employed as the traceable data acquisition unit for the metrological channels. Its 24-bit analog-to-digital conversion ca-

pability and configurable differential or single-ended input architecture enabled accurate acquisition of the pyranometer analog output. Under the considered measurement conditions, the quantization effects associated with the datalogger were negligible compared with the magnitude and variability of the irradiance signal. In addition, the battery-backed real-time clock of the CR1000X ensured stable timestamping over extended acquisition periods, which is a critical requirement for pointwise comparison between measured data and simulated trajectories.

A secondary PYR1307 pyranometer, Class C (Langlois, Gradignan Cedex, France) was also used as an auxiliary irradiance monitoring device, providing an independent plausibility check of the primary irradiance measurements. This secondary measurement channel was not treated as the main traceable reference but was useful for verifying the diurnal irradiance profile and the occurrence of cloud-induced variations. The comparison confirmed consistent trend-level behavior between the irradiance streams, while also indicating typical field-related limitations associated with pyranometer deployment, including leveling deviations, cosine response effects, tilt-dependent bias, and finite numerical resolution at the logger or display level.

The photovoltaic cell temperature $T_c(t)$ was acquired at one-minute resolution using a thin-film Pt100 resistance temperature detector manufactured according to IEC 60751 Class A specifications (RS Components Ltd., Corby, Northants, UK). The sensor was implemented as a surface-contact patch element and mounted on the rear surface of the photovoltaic module, in direct thermal contact with the backsheet. The IEC 60751 Class A tolerance, expressed as $\text{pm}(0.15 + 0.002 |T|)$ °C, provides a standards-based uncertainty contribution that can be explicitly included in the experimental error budget.

To reduce lead-wire resistance effects and improve measurement integrity over the cable length used in the experimental installation, the Pt100 sensor was connected to the CR1000X datalogger in a four-wire Kelvin configuration. The temperature acquisition was configured as a ratiometric resistance measurement with excitation polarity reversal, thereby reducing systematic offset errors, suppressing thermoelectric electromotive forces, and limiting the influence of long-term drift in excitation and contact potentials.

From a mechanical and thermal perspective, the sensing element was bonded to the module backsheet using a thermally conductive interface material in order to minimize contact thermal resistance. An aluminum patch and an insulating cover layer were applied above the sensing region to reduce the influence of convective disturbances, particularly wind-driven cooling. This configuration improved the representativeness of the measured backsheet temperature as an approximation of the photovoltaic cell temperature.

The temperature signal is a critical input for photovoltaic model validation because it directly affects the voltage-dependent terms of the model, including the open-circuit voltage $V_{OC}(T)$, the thermal voltage $V_T(T)$, and the temperature-dependent saturation current $I_0(T)$. Consequently, the synchronized acquisition of $T_c(t)$, $S(t)$, $V_{PV}(t)$, and $I_{PV}(t)$ preserves the coupled irradiance–temperature dynamics responsible for maximum power point displacement and real-time power variability during outdoor operation.

The metrological characteristics of the instrumentation chain used for the experimental model are reported in Table 2, with emphasis on the measurement range, resolution, accuracy, sensor-specific uncertainty, and acquisition parameters associated with each device, thereby ensuring the traceability, repeatability, and reliability of the experimental dataset used for model validation.

Table 2. Metrological characteristics of the instrumentation chain used for the experimental model.

Measurement Device	Acquired Quantity/Role in Validation	Metrological Performance and Uncertainty-Related Specifications
Class A pyranometer, ISO 9060:2018I	Tilted plane-of-array irradiance $S(t)$ [$\text{W}\cdot\text{m}^{-2}$]	The irradiance reference channel complied with ISO 9060 Class A requirements. The relevant limits include nonlinearity within $\pm 0.5\%$, spectral selectivity within $\pm 0.5\%$, temperature response within $\pm 1\%$ over $-10 \dots 40^\circ\text{C}$ relative to 20°C , tilt-response deviation within $\pm 0.5\%$ for $0\text{--}180^\circ$ at $1000 \text{ W}\cdot\text{m}^{-2}$, directional-response error up to $\pm 10 \text{ W}\cdot\text{m}^{-2}$, and annual non-stability below $\pm 0.8\%$. The zero-offset contributions were bounded by $\pm 7 \text{ W}\cdot\text{m}^{-2}$, $\pm 2 \text{ W}\cdot\text{m}^{-2}$, and $\pm 10 \text{ W}\cdot\text{m}^{-2}$ for offsets A, B, and C, respectively, while signal-processing effects were limited to approximately $\pm 2 \text{ W}\cdot\text{m}^{-2}$.
PYR1307 pyranometer	Secondary irradiance cross-check	Its specified measurement deviation was below $10 \text{ W}\cdot\text{m}^{-2}$ or 5% of the indicated value, whichever condition governed the operating range.
CR1000X Campbell Scientific	Analog voltage acquisition, ratiometric resistance measurement, wind velocity, rpm, irradiance, temperature and timestamp	For voltage measurements, the accuracy excluding external sensor and noise contributions was $\pm(0.04\%$ of reading + offset) over $0 \dots 40^\circ\text{C}$ and $\pm(0.06\%$ of reading + offset) over $-40 \dots 70^\circ\text{C}$. For ratiometric resistance measurements with input and excitation reversal and excitation below 1000 mV, the corresponding accuracy was $\pm(0.01\%$ of voltage measurement + offset) over $0 \dots 40^\circ\text{C}$ and $\pm(0.015\%$ + offset) over $-40 \dots 70^\circ\text{C}$.
Pt100 RTD	PV module backsheet temperature used as cell-temperature proxy $T_c(t)$ [$^\circ\text{C}$]	The temperature sensing element complied with IEC 60751 Class A requirements. The admissible element tolerance was expressed as $\pm(0.15 + 0.002 T)$ $^\circ\text{C}$, providing the standards-based contribution of the RTD to the thermal measurement uncertainty budget.
03101-L Wind Sentry Anemometer	Instantaneous wind velocity $v_1(t)$ [m/s]	The device is based on a three-cup rotor assembly and operates over a measurement range of $0\text{--}50 \text{ m/s}$, with gust survivability up to 60 m/s . The specified wind-speed accuracy is $\pm 0.5 \text{ m/s}$, while the starting threshold is 0.5 m/s . The transduction mechanism consists of a stationary coil excited by a rotating magnet mounted on the cup-wheel shaft, generating an AC sine-wave signal with one cycle per cup-wheel revolution. The output frequency is proportional to wind speed, with a conversion factor of 0.75 m/s per Hz , enabling direct frequency-based acquisition through the datalogger pulse-count channel [35].
Monarch ROS-W Remote Optical Sensor	Rotor rotational speed, $n(t)$ [rpm]	The sensor operates over a speed range of $1\text{--}250,000 \text{ rpm}$ and uses a visible red LED optical beam for detecting the passage of a reflective target attached to the rotating shaft, hub, or auxiliary rotor disc. Proper alignment is verified by an integrated green on-target indicator. The permissible operating distance extends up to 0.9 m , with a maximum optical offset of 45° from the target axis. The sensor provides a negative pulse output referenced from (+V) to 0 V, suitable for frequency or pulse-count acquisition. The operating temperature range is $-10 \dots 70^\circ\text{C}$, allowing its use in controlled laboratory tests and moderate outdoor experimental campaigns [36].

The complete experimental architecture will be further extended by considering the wind-energy conversion subsystem and its associated equipment. However, for methodological clarity, the hybrid system is analyzed progressively at subsystem level. Therefore, the present subsection is restricted to the photovoltaic subsystem, while the wind-turbine subsystem, including its measurement, conversion, control, and storage-related interfaces, will be treated separately in the following section.

For the wind-energy conversion subsystem, the incident wind speed at the turbine inlet can be measured using a 03101-L Wind Sentry anemometer (Campbell Scientific, Logan, UT, USA), interfaced directly with the CR1000X datalogger through a pulse-count/frequency input. Wind speed was measured close to the turbine installation area in order to characterize the local inflow conditions. The measured wind speed may include site-specific turbulence and local flow disturbances; therefore, the WT results should be interpreted as experimental performance under the tested configuration, not as a generalized turbine power curve. The sensor generates an AC signal whose frequency is proportional to the cup-wheel rotational speed, enabling conversion of the measured frequency into the instantaneous wind velocity ($v_1(t)$). This configuration provides a direct time-domain input for the aerodynamic model of the turbine and allows synchronization with the electrical and thermal variables already acquired by the same data acquisition platform.

The rotor speed can be acquired by means of a non-contact tachometric sensor mounted in proximity to the turbine shaft. A suitable solution is the ROS-W Remote Optical Sensor (Monarch Instrument, Amherst, NH, USA), which generates one pulse per passage of a reflective target and can therefore be connected to CR1000X pulse-count channel for determining the rotor speed, $n(t)$. In this configuration, the sensor provides a square-wave pulse train whose frequency is proportional to rotor angular speed, allowing the determination of $n(t)$ [rpm] or angular velocity, $\omega_r(t)$ [rad·s⁻¹] under both steady-state and transient operating regimes.

Thus, the CR1000X acquisition unit provides the common synchronized measurement backbone for the photovoltaic and wind subsystems, ensuring coherent timestamping of irradiance, temperature, wind speed, and rotor-speed data.

In parallel, the Cerbo-S GX (Victron Energy B.V., Almere, The Netherlands) (Figure 3) operates as the supervisory monitoring and integration interface of the hybrid experimental platform via VE.Direct cables, consolidating the operational data delivered by the connected Victron devices and sensors, while the traceability of the environmental and metrological channels remains assigned to the CR1000X-based acquisition chain. Battery-side electrical monitoring was performed using SmartShunt 500 A/50 mV modules (Victron Energy B.V., Almere, The Netherlands), which enabled high-resolution acquisition of current, voltage, and state-of-charge parameters. The measured data were transmitted to the supervisory acquisition layer through the VE.Direct interface, ensuring continuous tracking of the electrochemical storage subsystem during experimental operation.

Figure 4 illustrates the telemetry-based monitoring of the hybrid WT–PV prototype, showing the instantaneous power contributions of the photovoltaic subsystem, the wind-turbine subsystem, and the resulting aggregate hybrid output. The data were acquired through the VE.Direct communication interface between the PV MPPT controller, the wind-side SmartShunt 500 A/50 mV unit, and the Cerbo-S GX monitoring platform. The recorded profiles highlight the variable and complementary behavior of the two renewable sources, with the PV subsystem providing the dominant contribution during periods of increased solar availability, while the wind subsystem introduces short-term power fluctuations associated with local wind-speed variability. Consequently, the figure provides experimental evidence of the dynamic power-sharing mechanism within the common DC architecture of the hybrid renewable-energy system.

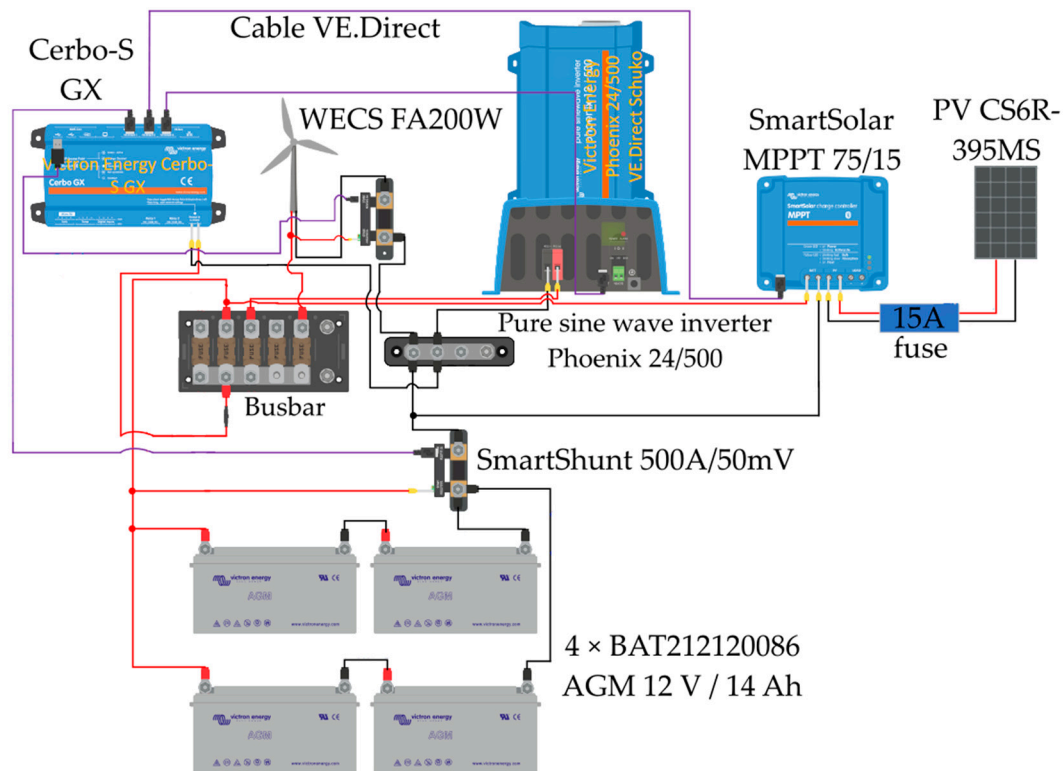


Figure 3. Implementation of the Cerbo-S GX monitoring unit using VE.Direct communication links.

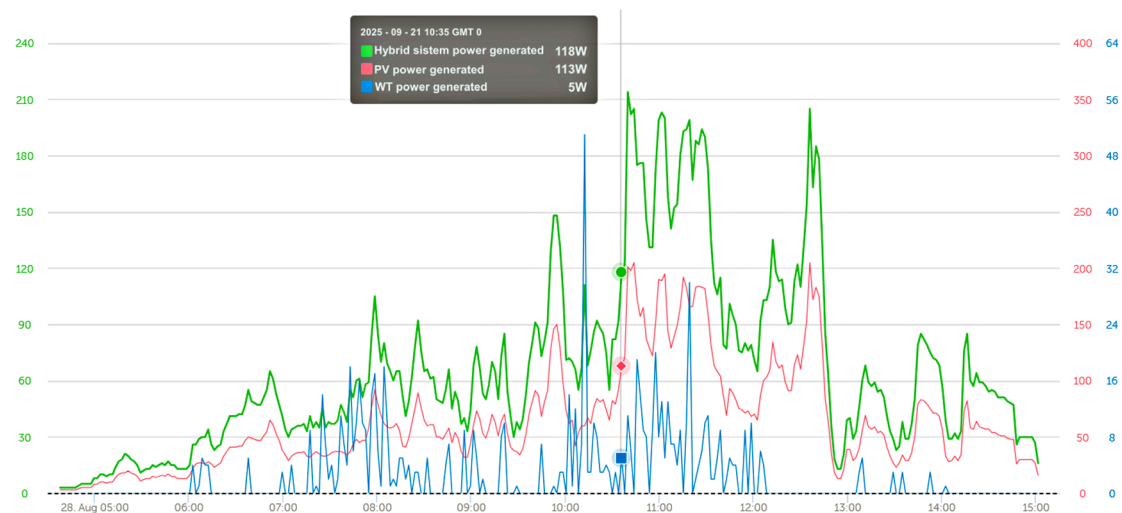


Figure 4. Representative telemetry-dashboard screenshot showing the VE.Direct communication link between the PV MPPT controller, the wind-side SmartShunt 500 A/50 mV unit, and the Cerbo-S GX monitoring interface.

4. Mathematical Model of the Hybrid System

4.1. Aerodynamic and Electrical Modelling of the WECS

When the air density, effective swept area, and wind velocity are known, the theoretical power contained in the wind stream can be determined and expressed in watts [37]. This available wind power is given by:

$$P_{available}(v_1) = \frac{\rho \Pi R^2 v_1^3}{2} \quad (1)$$

where ρ denotes the air density, R represents the rotor radius in meters, and v_1 indicates the wind speed.

The electrical output of a wind turbine is determined by the kinetic energy carried by the incoming air stream and by the power coefficient, C_p , which expresses how effectively the turbine converts the available wind energy into usable power. On this basis, the instantaneous mechanical power captured from the wind may be written as [37]:

$$P_{\text{mechanical}}(\omega_r, \beta, v_1) = C_p(\delta, \beta) \cdot \frac{\rho \Pi R^2 v_1^3}{2} \quad (2)$$

where ω_r denotes the rotor's angular speed in rad/s, β represents the blade-pitch angle in degrees, and δ indicates the tip-speed ratio (TSR).

The power coefficient C_p is a standard measure of wind-turbine aerodynamic efficiency, quantifying what fraction of the incoming wind power is converted into useful mechanical power at the rotor. Due to basic momentum-theory constraints, this conversion ratio has an upper bound of about 59%, commonly referred to as the Betz limit. As a result, even under ideal conditions, a turbine can extract only part of the kinetic energy carried by the airflow [38,39].

$$C_p(\delta, \beta) = x_1 \left(\frac{x_2}{\delta_i} - x_3 \beta - x_4 \right) e^{\frac{-x_5}{\delta_i}} + x_6 \delta \quad (3)$$

The study incorporates established standard parameters for the component under evaluation for the parameters x_1 to x_6 are as follows: $x_1 = 0.5176$, $x_2 = 116$, $x_3 = 0.4$, $x_4 = 0$, $x_5 = 21$, and $x_6 = 0.0068$.

The aerodynamic behavior of a wind turbine is governed by the interaction between the power coefficient and the tip-speed ratio (TSR), δ , defined as the ratio between the blade tip peripheral speed and the incoming wind velocity [37–41].

$$\delta(\omega_r, v_1) = \frac{v_t}{v_1} = \frac{\omega_r * R}{v_1} \quad (4)$$

δ_i is defined as:

$$\delta_i(\omega_r, v_1, \beta) = \left[\frac{1}{\frac{\omega_r R}{v_1} + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \right]^{-1} \quad (5)$$

Consequently, by integrating Equations (2)–(5), the electrical active power produced by the wind turbine is defined as follows:

$$P_{WT}(\omega_r, v_1, \beta) = \eta_m \eta_e \eta_{aux} \frac{\rho \Pi R^2 v_1^3}{2} \left[0.5176 \left(116 \left[\frac{1}{\frac{\omega_r R}{v_1} + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \right] - 0.4\beta \right) e^{-21 \left[\frac{1}{\frac{\omega_r R}{v_1} + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \right]} + 0.0068 \frac{\omega_r R}{v_1} \right] \quad (6)$$

where the following efficiency factors are considered [37]:

η_m denotes the overall mechanical efficiency of the drivetrain;

η_e represents the electrical generator's conversion efficiency;

η_{aux} represents the efficiency of the auxiliary circuits, encompassing losses in the wind-turbine controller electronics.

4.2. Physics-Based Mathematical Modelling of the PV Conversion System

The terminal current I delivered by a photovoltaic cell can be described as the net result of the photogenerated current I_L , reduced by the internal loss mechanisms associated with the diode branch and the shunt path. In the equivalent electrical model, I_L represents the current produced by the incident solar radiation through the photovoltaic effect, while

I_D accounts for the recombination-related current flowing through the p-n junction diode. In addition, a parasitic shunt current I_{sh} flows through the shunt resistance R_{sh} , reducing the useful output current available at the external terminals [42].

The shunt current is generally associated with non-idealities of the photovoltaic junction, including localized defects, crystal imperfections, edge leakage paths, or technological imperfections occurring during cell manufacturing. The parameter R_{sh} therefore characterizes the degree of isolation of the junction against parasitic leakage currents. A high value of R_{sh} is desirable, since it limits leakage losses and improves the current–voltage characteristic, particularly in the low-voltage operating region [42–47].

Figure 5 presents the single-diode equivalent circuit model used to describe the electrical behavior of the PV module. The model includes the photocurrent source, the diode representing the p–n junction, the series resistance (R_S), and the shunt resistance (R_{sh}), which account for internal ohmic losses and leakage-current effects. This representation provides the theoretical basis for estimating the current–voltage characteristic of the photovoltaic module and for evaluating its power output under variable irradiance and temperature conditions.

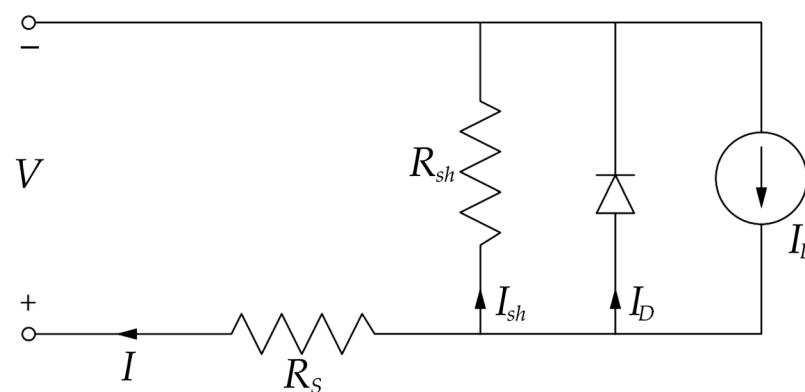


Figure 5. Single-diode equivalent circuit model of the PV Module [41].

The series resistance R_S represents the cumulative ohmic resistance encountered by the generated charge carriers along their path toward the external circuit. This resistance includes contributions from the semiconductor bulk, the p–n junction region, the metallic contacts, the front and rear electrodes, and the interconnection conductors. Its value is influenced by the structural and technological properties of the solar cell, such as the thickness of the p–n junction, the doping profile, the concentration of impurities, and the quality of the electrical contacts [42–47].

For an ideal photovoltaic cell, the series resistance is assumed to be zero, $R_S = 0$, while the shunt resistance tends toward infinity, $R_{sh} \rightarrow \infty$. Under these theoretical conditions, no ohmic voltage drop occurs in the current path and no leakage current is diverted through parasitic shunt branches. Real photovoltaic cells, however, always exhibit finite values of R_S and R_{sh} , which directly affect their electrical behavior and energy conversion capability [42].

In high-quality crystalline silicon photovoltaic cells, typical values of the series resistance are commonly in the range of 0.05–0.10 Ω , whereas the shunt resistance may reach values of approximately 300–400 k Ω . Among these two parasitic parameters, the series resistance has a more pronounced influence on the conversion efficiency, since even small increases in R_S lead to additional ohmic losses, a reduction in the fill factor, and a decrease in the maximum power point. By contrast, variations in R_{sh} generally have a less significant effect on efficiency, provided that the shunt resistance remains sufficiently high to suppress leakage currents [42].

The fundamental equation describing the equivalent circuit of a single-diode photovoltaic cell, illustrated in Figure 5, is obtained by applying Kirchhoff's current law to the output current I [42–47]:

$$I = I_L - I_D - I_{sh} \quad (7)$$

where I represents the generated output current, I_L is the photocurrent produced in the cell under illumination, I_D denotes the voltage-dependent current loss through the diode, and I_{sh} is the leakage current associated with the shunt resistance.

The light-generated current of the photovoltaic cell can be expressed as [42]:

$$I_L = \left[I_{sc} + K_i (T_c - T_{ref}) \right] \cdot \frac{S + S \cdot Alb(1 - \cos \theta)}{1000} \quad (8)$$

where I_{sc} denotes the short-circuit current under the considered operating temperature, K_i is the temperature coefficient associated with the short-circuit current, T_c represents the cell temperature, expressed in Kelvin (K), and T_{ref} is the reference temperature, also expressed in Kelvin (K). Furthermore, S indicates the incident solar irradiance, Alb represents the ground-reflected irradiance contribution through the albedo factor, and θ is the angle of incidence of the solar rays on the photovoltaic module surface.

In the single-diode equivalent circuit, the diode current I_D is commonly represented by the Shockley equation for an ideal diode, as follows [42–47]:

$$I_D = I_0 \left(e^{\frac{V + IR_s}{nV_T}} - 1 \right) \quad (9)$$

where I_0 denotes the reverse saturation current of the diode, n is the diode ideality factor, a dimensionless parameter that typically ranges from 1 to 2 for a single-junction photovoltaic cell, V represents the cell terminal voltage, and R_s is the series resistance of the equivalent circuit [42–47].

The shunt current I_{sh} , which accounts for the current loss through the parallel leakage path of the photovoltaic cell, can be determined using the following relation [42–47]:

$$I_{sh} = \frac{V + IR_s}{R_{sh}} \quad (10)$$

where R_{sh} represents the shunt resistance of the equivalent circuit.

For a DC system, the electrical power is defined as:

$$P_{PV} = V \cdot I \quad (11)$$

where P is the generated electrical power, V is the voltage, and I is the current. For a photovoltaic array composed of identical modules, series connections increase the output voltage, while parallel connections increase the output current. Therefore, A denotes the number of modules connected in series, and B denotes the number of parallel branches.

By combining the DC power relation with the single-diode photovoltaic model, the generated photovoltaic power can be expressed as:

$$P_{PV} = VA \left\{ \left[I_{sc} + K_i (T_c - T_{ref}) \right] \cdot \frac{S + S \cdot Alb(1 - \cos \theta)}{1000} - I_0 \left(e^{\frac{V + IR_s}{nV_T}} - 1 \right) - \frac{V + IR_s}{R_{sh}} \right\} B \quad (12)$$

The first term represents the irradiance and temperature-dependent photocurrent, the second term describes the diode-related current loss, and the third term accounts for the shunt leakage current. The coefficients A and B scale the model according to the number of series-connected modules and parallel-connected strings, respectively.

4.3. Numerical Simulation Framework

For the photovoltaic subsystem, the albedo coefficient was treated as a constant parameter, while the model inputs comprised solar irradiance, cell temperature, experimentally measured voltage, and the computed solar-incidence angle on the photovoltaic module surface.

In accordance with the experimental setup, the simulation framework considers data acquisition through the solar charge controller, which interfaces with both the photovoltaic module input and the battery-bank output. Although the mathematical formulation primarily characterizes the electrical behaviour of the photovoltaic generator, the final validation of the hybrid system requires the assessment of the energy effectively transferred to the storage unit. Consequently, the efficiency of the solar charge controller must be included in the simulation block diagram. Under this assumption, the photovoltaic power expression (12) becomes:

$$P_{PV} = VA \left\{ \left[I_{sc} + K_i (T_c - T_{ref}) \right] \cdot \frac{S + S \cdot Alb(1 - \cos \theta)}{1000} - I_0 \left(e^{\frac{V + IR_s}{nV_T}} - 1 \right) - \frac{V + IR_s}{R_{sh}} \right\} B\eta_{mppt} \quad (13)$$

where η_{mppt} denotes the efficiency of the solar charge MPPT controller.

For the wind energy subsystem, the simulation incorporated the complete efficiency chain associated with power conversion. This included the mechanical losses occurring in the transmission stage, as well as the conversion efficiencies of the synchronous generator and the wind charge controller. Therefore, the wind model was configured to estimate the net electrical power delivered to the storage system rather than only the theoretical mechanical power extracted from the turbine shaft.

When two renewable-energy conversion subsystems are coupled to a common DC distribution bus, the net generated power can be obtained by superimposing the power contributions of each source, provided that the electrical interface, voltage level, and control strategy ensure proper coordination and synchronization of the sources [30–33]. Therefore, by combining the wind power model given by Equation (6) with the photovoltaic power model defined in Equation (13), the useful electrical power supplied by the hybrid renewable-energy system can be expressed as the cumulative output delivered to the common bus:

$$P_{hybrid} = \eta_m \eta_e \eta_{aux} \frac{\rho I R^2 v_1^3}{2} \left\{ 0.5176 \left[116 \left(\frac{1}{\frac{2II_{in} \cdot R}{60v_1} + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \right) - 0.4\beta \right] e^{-21 \left(\frac{1}{\frac{2II_{in} \cdot R}{60v_1} + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \right)} + 0.0068 \frac{2II_{in} \cdot R}{60v_1} \right\} \\ + VA \left\{ \left[I_{sc} + K_i (T_c - T_{ref}) \right] \cdot \frac{S + S \cdot Alb(1 - \cos \theta)}{1000} - I_0 \left(e^{\frac{V + IR_s}{nV_T}} - 1 \right) - \frac{V + IR_s}{R_{sh}} \right\} B\eta_{cont} \quad (14)$$

The simulation scenario was defined by introducing the experimentally derived variables previously described as time-dependent input parameters. To reduce the complexity of the numerical model while preserving its relevance for system-level assessment, the conversion efficiencies of the main components were implemented as lumped efficiency factors. This approach enabled the evaluation of the overall energetic performance of the hybrid renewable-energy system under experimentally representative operating conditions.

In the PV modelling sequence, the final Simulink implementation was configured to determine the module terminal current by solving the complete single-diode current-balance formulation. The assembled computational structure combines the irradiance-, temperature-, and geometry-dependent photocurrent component $I_L(S, T, \theta, \beta)$, the non-linear diode-recombination current $I_D(V, T)$, and the shunt-leakage contribution $I_{sh}(V)$, while the effects of R_s and R_{sh} are represented through the internal voltage correction and the parallel leakage pathway. Consequently, the photovoltaic current is obtained from the

information. Therefore, the drivetrain losses were estimated from representative small-turbine loss mechanisms, namely bearing friction and internal aerodynamic drag. Considering approximately 2% power loss in good-quality modern bearings and an additional 1% loss due to air friction around rotating components, the overall mechanical efficiency of the transmission path was set to ($\eta_m = 0.97$). Based on the technical specifications of the experimental equipment, the generator efficiency was defined as ($\eta_e = 0.95$), while the auxiliary-circuit efficiency was represented by the wind-controller efficiency, ($\eta_{aux} = 0.97$), since the system does not include an industrial-grade auxiliary conversion architecture. These coefficients were implemented in the Simulink block diagram to compute the useful electrical power delivered by the wind turbine.

Figure 7 presents the simulated dynamic power response of the PV generator, wind turbine, and aggregated PV–WT hybrid energy system, obtained using the mathematical model implemented in MATLAB/Simulink (R2023a). The PV subsystem provides the dominant contribution to the total hybrid output, with power variations mainly governed by the modeled irradiance and temperature-dependent operating conditions, whereas the wind-turbine contribution remains intermittent and is characterized by short-duration power peaks associated with the simulated wind-speed profile. The close correspondence between the PV generator power curve and the total hybrid power profile indicates that, under the analyzed scenario, the hybrid output is primarily driven by the photovoltaic subsystem, while the wind subsystem provides additional power during favorable wind conditions. These simulated results provide a preliminary assessment of the transient power availability of the proposed low-power maritime hybrid renewable-energy system prior to experimental validation.

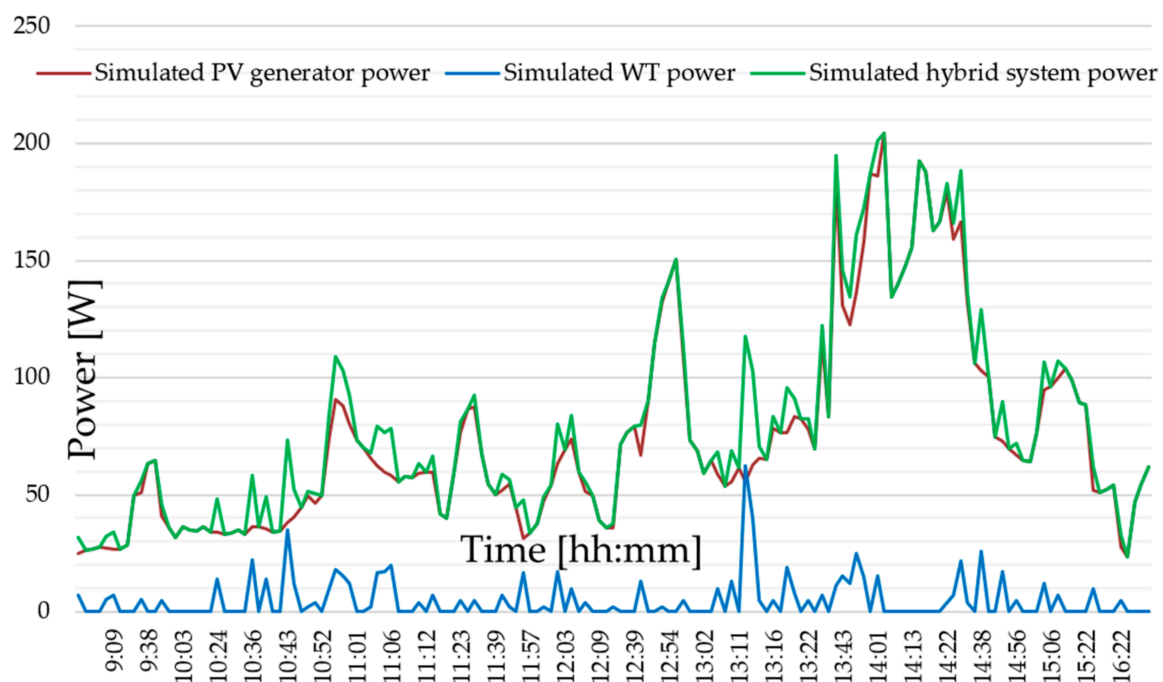


Figure 7. Dynamic simulated power response of the PV generator, WT, and hybrid PV–WT energy system.

Following the numerical simulation of the wind–photovoltaic hybrid system, the obtained results provide an initial assessment of the theoretical operating behaviour of the proposed configuration under different operating scenarios. The simulated datasets enable the preliminary evaluation of the available energy potential, the dynamic power response, and the overall conversion performance of the integrated renewable-energy system.

At this stage, however, the numerical results represent only a model-based prediction and cannot be considered experimentally validated. Therefore, a systematic comparison with field-acquired measurements is required in order to quantify the prediction accuracy, identify possible deviations between the simulated and measured responses, and confirm the technical reliability and applicability of the developed theoretical model.

4.4. Model Parameterization and Validation Procedure

The model parameters were defined from manufacturer datasheets, measured system configuration, and experimentally recorded environmental variables. No post-processing adjustment was applied to force agreement between measured and simulated hybrid output power. The validation was performed by comparing the simulated hybrid power with the measured power recorded by the monitoring system over the selected experimental interval. The data were acquired at a sampling interval of 60 s. For the complete experimental campaign conducted from 15 to 24 September 2025, the validation dataset comprised $N = 14,400$ time-synchronised pairs of simulated and measured power values, corresponding to 240 h of continuous monitored operation. These paired observations were used to calculate the ME, MAE, RMSE, and MAPE performance indicators.

5. Experimental Operation of the Hybrid RES Prototype Under Variable Maritime Loads and Case Study

5.1. Experimental Campaign and Selected Representative Interval

The experimental measurements were collected between 15 September 2025 and 24 September 2025 under a wide range of atmospheric conditions, including clear-sky intervals and periods with intermittent cloud cover, to ensure sufficient excitation diversity for robust model assessment. Model validation was performed over the entire campaign dataset, and the reported error indicators (e.g., bias) were computed using the full population of recorded samples. The experimental campaign was performed on board, with the turbine and PV panel exposed to natural wind conditions.

The experimental interval corresponding to 21 September 2025 was deliberately selected because the prevailing meteorological conditions enabled a representative assessment of the hybrid PV–wind system under complementary source behavior. The high cloud-cover fraction, approximately 7/8, imposed a substantial reduction in photovoltaic conversion performance, while the moderate wind gusts recorded during the same interval provided suitable excitation for acquiring the main operating variables of the wind-energy conversion subsystem. This combination of reduced solar input and usable wind availability generated an appropriate test case for evaluating hybrid-system operation under non-uniform atmospheric conditions.

The analysis focused on the principal wind-turbine variables and on the photovoltaic power limitation induced by cloud attenuation. Under these conditions, the experimental dataset allowed the interaction between the two renewable sources to be assessed in terms of power complementarity, energy-conversion continuity, and subsystem-level contribution to battery charging. The measurements were therefore used to support the comparison with the theoretical simulations and to validate the hybrid-system response under variable meteorological forcing.

5.2. Hybrid PV–Wind Power Production Under Variable Environmental Inputs

During the experimental campaign, the data acquisition system recorded, at 60 s sampling intervals. These measurements enabled the computation of the generated current under actual outdoor operating conditions and provided the experimental dataset required for model parameterization and validation. In order to improve the fidelity of the numerical

analysis, the simulation inputs were derived primarily from measured quantities rather than from nominal manufacturer data.

The accuracy of the simulated results was evaluated by calculating the absolute relative error (ARE) between the experimental and simulated quantities, according to:

$$ARE = \frac{|Value_{empirical} - Value_{simulated}|}{|Value_{empirical}|} \cdot 100 \quad [\%] \quad (15)$$

The resulting error values, obtained from the experimental and simulation-based datasets, are summarized in the previous table. This comparison provides a quantitative assessment of the predictive capability of the developed model. For validation purposes, the relative error was considered acceptable when it remained below the prescribed 10% threshold.

Table 3 summarizes the point-by-point validation framework of the hybrid WT–PV system, in which the wind-side variables (v_1) and (n), the PV-side model input conditions (S), (T), and (θ), and the experimentally acquired operating voltage (V) are jointly used to compute and compare the simulated power outputs with the corresponding field-measured values. This structure provides a coherent basis for validating (P_{sim}) against (P_{real}) at wind-turbine, photovoltaic, and total hybrid-system levels, while the absolute relative error (ARE) quantifies the predictive consistency of the model under variable operating conditions.

Table 3. Simulated versus experimental performance of the Hybrid WT–PV system under variable operating conditions.

Wind Turbine Data				PV Panel Data				Hybrid System Data				
v_1 [m/s]	n [rot/min]	P_{sim} [W]	P_{real} [W]	S [W/m ²]	T [°C]	θ [°]	V [V]	P_{sim} [W]	P_{real} [W]	P_{sim} [W]	P_{real} [W]	ARE [%]
4	137	6.98	7.76	83	22	73.92	28.09	24.78	23.21	31.76	31	2.68
0	0	0.00	0.00	84	22	73.67	29.89	26.28	25.78	26.28	26	1.08
3.9	117	5.06	5.37	147	23	65.71	29.38	50.89	50.86	55.96	56	0.07
4.8	164	12.00	12.92	210	27	45.61	31.55	80.33	80.32	92.33	93	0.72
5.3	185	16.95	17.81	163	27	44.39	31.06	59.47	60.74	76.42	76	0.55
0	0	0.00	0.00	168	27	43.91	27.65	55.62	57.55	55.62	55	1.13
3.3	69	2.01	2.42	110	29	24.34	29.87	35.84	36.36	37.85	38	0.39
9.5	253	62.27	62.59	156	31	13.94	30.58	55.43	55.80	117.69	118	0.26
4.1	136	7.02	7.77	302	32	8.65	30.49	115.11	119.19	122.13	122	0.11
4.7	159	11.02	11.17	465	32	7.47	30.89	183.97	190.13	194.99	194	0.51
6.1	209	24.77	25.26	351	32	5.18	30.78	136.26	141.01	161.03	161	0.02
0	0	0.00	0.00	535	32	4.77	29.61	204.38	210.01	204.38	204	0.19
0	0	0.00	0.00	442	31	6.03	29.51	166.36	168.98	166.36	166	0.22
4.8	164	12.00	12.95	258	29	15.26	29.97	94.70	95.65	106.69	106	0.65

The operating points reported in Table 3 correspond to the experimental interval recorded on 21 September 2025, which was selected for detailed tabular and graphical presentation because it represented a challenging hybrid operating condition, with reduced photovoltaic availability caused by high cloud cover and variable wind-turbine contribution. These rows are presented as representative validation examples and do not constitute the full dataset used for error assessment. The complete synchronized dataset acquired during the 15–24 September 2025 experimental campaign was used for the global validation analysis, and across this full campaign the maximum absolute relative error remained below 2.69%.

The selection does not imply data exclusion or preferential reporting; rather, it serves an editorial purpose by avoiding the excessive visual density that would arise from displaying the complete multi-week experimental dataset. At the same time, the chosen interval preserves the characteristic diurnal operating profile and enables a concise, trace-

able, and reproducible comparison between the experimentally measured responses and the simulated trajectories.

The discrepancy between the sum of the experimentally determined active-power contributions of the PV and wind subsystems and the real active power reported for the overall hybrid system can be attributed to the fact that these quantities are not necessarily acquired at the same energetic node of the architecture, but rather at different branches and interfacing stages of the system. Thus, although the renewable-source-side available power results from the complementary contribution of the photovoltaic subsystem and the wind turbine, the hybrid power displayed by the monitoring platform may also incorporate the effects of conversion and transfer losses, particularly those associated with the 24 V DC/230 V AC inverter, the MPPT controllers, electrical conductors, contact resistances, and SmartShunt-based measurement devices.

In addition, the values reported by the monitoring equipment are affected by finite numerical resolution and internal estimation or rounding algorithms, which may generate pointwise deviations between the arithmetic sum $P_{PV,real} + P_{WT,real}$ and the telemetered value of $P_{hyb,real}$. Therefore, for the analysed operating point, the experimental source-side contributions of 190.13 W from the PV subsystem and 11.17 W from the wind turbine yield an aggregated complementary power of approximately 201.3 W, whereas the reported hybrid value of 194 W represents the effective power available after conversion, transfer, and monitoring-related losses within the real system architecture.

For enhanced manuscript readability and improved graphical interpretability, the dataset recorded on 21 September 2025 was selected for presentation in the corresponding figures and tables. This day was characterized by reduced solar irradiance and moderate wind conditions, the hybrid system reached a maximum combined power output of 204 W, while the Simulink-based mathematical model predicted 204.38 W. The minimum combined power recorded experimentally was 26 W, compared with a simulated value of 26.28 W, indicating close agreement between the measured and model-derived power profiles (Figure 8).

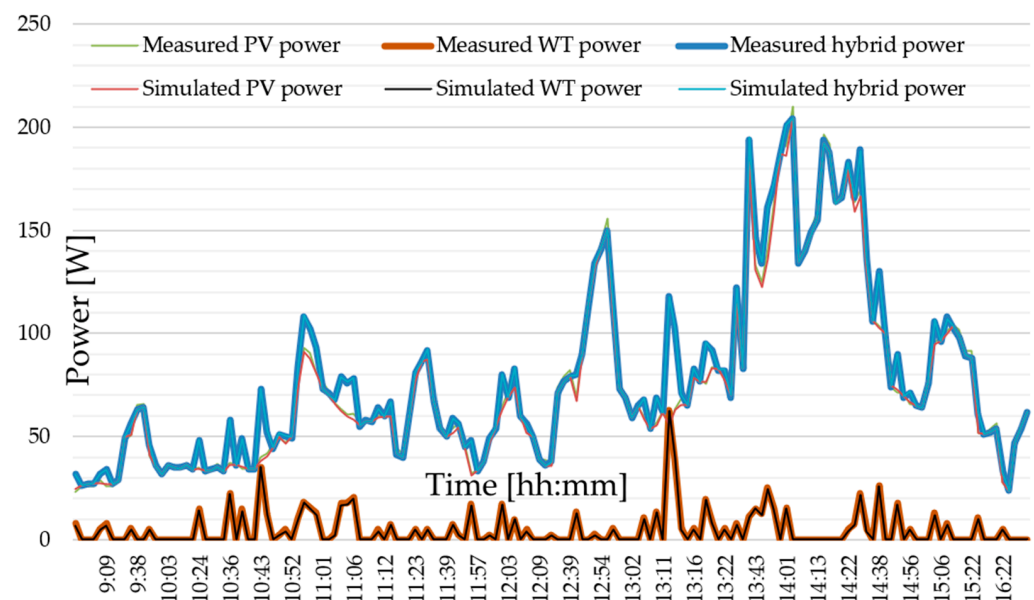


Figure 8. Measured and simulated power profiles of the PV, WT, and hybrid PV–WT system.

At subsystem level, the experimental wind-turbine output ranged from 2.42 to 62.59 W, according to the measured wind-speed variations, whereas the simulated wind-power values ranged from 2.01 to 62.27 W. For the photovoltaic subsystem, the measured output

power varied between 23.21 and 210.01 W, as a function of solar irradiance, cell temperature, and incidence angle on the module surface. The corresponding Simulink model predicted PV power values between 24.78 and 204.38 W, confirming the capability of the proposed mathematical model to reproduce the hybrid-system response under variable environmental excitation.

The primary objective was to validate the simulation-derived results against the experimental datasets acquired during the testing campaign. Within this validation framework, the relative error remained below 2.69%, indicating a high level of numerical accuracy and confirming the consistency between the mathematical model and the measured operating performance of the hybrid energy system.

5.3. Statistical Error Assessment

The accuracy of the simulated results can be further quantified using four statistical error indicators (Table 4): the mean error (ME-bias), the mean absolute error (MAE), the root mean square error (RMSE), and the mean absolute percentage error (MAPE), defined as follows:

$$ME = \frac{1}{n} \sum_{i=1}^n (y_{i,\text{exp}} - y_{i,\text{sim}}) \quad (16)$$

$$MAE = \frac{1}{n} \sum_{i=1}^n |y_{i,\text{exp}} - y_{i,\text{sim}}| \quad (17)$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_{i,\text{exp}} - y_{i,\text{sim}})^2} \quad (18)$$

$$MAPE = \frac{100}{n} \sum_{i=1}^n \left| \frac{y_{i,\text{exp}} - y_{i,\text{sim}}}{y_{i,\text{exp}}} \right| \quad (19)$$

where $y_{i,\text{exp}}$ denotes the experimentally measured value, $y_{i,\text{sim}}$ represents the corresponding simulation-derived value, and n is the total number of paired observations. ME indicates the average signed deviation and is used to identify systematic overestimation or underestimation of the model. MAE quantifies the average magnitude of the absolute deviations, RMSE assigns greater weight to larger deviations due to the quadratic penalty, whereas MAPE expresses the average normalized error as a percentage of the experimental reference values.

Table 4. Statistical validation indices for the active-power response of the hybrid energy system.

Output	ME (Bias)	MAE	RMSE	MAPE [%]
Power $P(t)$ [W]	−0.1041	0.3988	0.4931	0.5946
Mean ± SD	−0.104 ± 0.03	0.399 ± 0.04	0.493 ± 0.05	0.595 ± 0.07

Note: The error indicators were evaluated over the complete experimental campaign conducted between 15 September 2025 and 24 September 2025, using time-aligned datasets acquired at 1 min sampling resolution. The reported SD values quantify the day-to-day variability of the error metrics around their corresponding campaign mean values.

Based on the paired simulated and experimental active-power values of the hybrid system, the statistical validation indicators confirm a very high agreement between the numerical model and the measured response. The mean error, $ME = -0.1041$ W, indicates an almost negligible systematic bias over the analysed dataset. The negative sign shows that the simulation slightly overestimates the measured hybrid-system output power, although the magnitude of this bias is technically insignificant when compared with the operating power range of the system. The MAE value of 0.3988 W demonstrates that the average absolute deviation between the simulated and experimental power values remains below 0.4 W. This result indicates that the model preserves a high point-by-point predictive

accuracy and that the absolute discrepancies between the two datasets are minimal across the full set of synchronized measurements.

The RMSE value of 0.4931 W further confirms the numerical stability of the developed model. Since RMSE is only slightly higher than MAE, the validation dataset does not contain dominant high-amplitude deviations or isolated error peaks capable of significantly degrading the model response. This behaviour indicates that the simulated power profile follows the experimental power dynamics with consistent accuracy under variable irradiance, wind-speed, and hybrid operating conditions. The MAPE value of 0.5946% provides a normalized assessment of the prediction error and confirms that the average relative deviation remains well below both the 2.69% validation limit and the commonly accepted 10% engineering threshold. Therefore, the simulation framework can be considered highly representative of the real operating behaviour of the hybrid PV–wind energy system, with a strong quantitative correlation between the simulated and experimentally measured active-power outputs.

5.4. Representative On-Board Load Profile

The experimental load states were systematically correlated with actual onboard consumers of a small marine vessel (5.7 m LOA), establishing a technically grounded correspondence between the imposed power levels and real auxiliary electrical demand. The DC component of each load state was mapped to representative low-power consumers drawn from the vessel’s navigation, communication, lighting, and monitoring subsystems, supplied from the 24 V battery bus. The AC component was characterized as an aggregated inverter-fed auxiliary demand, encompassing loads supplied through the DC/AC conversion stage.

Table 5 reports the onboard consumer inventory used for load-state mapping, linking each representative auxiliary device to its operational category, supply interface, and nominal power requirement, thereby enabling a physically consistent correspondence between the experimentally applied DC/AC load levels and the expected electrical demand profile of a 5.7 m LOA small marine vessel.

Table 5. Onboard consumer inventory of the small marine vessel (5.7 m LOA) used for load-state mapping.

Navigation Equipment	Unit Power (W)	Qty.	Remarks
GPS Garmin GPSMAP 923xsv	15	1	Essential
Radar Garmin GMR 18 HD+	15	1	
AIS Transponder Garmin AIS 800	4	1	Active during navigation
Garmin GMC 010-compass	1	1	
Echosounder Lowrance HOOK2-5	3	1	
NASA Marine Clipper	1	1	
Communication Systems			
Standard Horizon GX2200 fixed VHF radio	6	1	Continuous stand-by
Icom IC-M25 portable VHF radio	3	1	Backup
EPIRB McMurdo E5 406 MHz	0.5	1	Emergency only
Lighting Circuits			
LED navigation lights (starboard + port + stern)	10	1	Mandatory at night
LED anchor position light (360°)	5	1	Mandatory at anchor
12 V AC/DC LED strip cabin interior lighting	20	1	Evening/night

It should be noted that the proposed consumer-to-load-state mapping does not resolve the discrete switching sequences of individual onboard devices at each measurement times-

tamp; rather, it constitutes a technically consistent equivalent load-allocation framework, intended to provide maritime operational relevance to the experimentally acquired energy balance data and to enable the interpretation of hybrid PV–wind system performance under realistic small-vessel auxiliary demand conditions.

5.5. DC/AC Load-State Mapping

The photovoltaic–wind hybrid system investigated in this study was designed as an auxiliary renewable-energy unit intended to support selected low-power marine consumers through a 24 V battery-based DC architecture. The proposed configuration is therefore not treated as the primary propulsion or main electrical supply of the vessel, but rather as a complementary power subsystem dedicated to auxiliary onboard loads whose operation depends on the navigation mode, harbour or anchorage conditions, and the instantaneous availability of solar and wind resources.

To assign maritime operational relevance to the experimental loading procedure, the applied load states were mapped to representative DC and AC consumers typically found on a 5.7 m LOA small marine vessel. The DC-side loads were associated with navigation, communication, lighting, and monitoring equipment supplied directly from the 24 V battery bus. In contrast, the AC-side loads were represented as aggregated inverter-fed auxiliary demand, corresponding to consumers supplied through the DC/AC conversion stage. This approach provides an equivalent load-allocation framework that enables the experimentally measured power flows to be interpreted in relation to realistic onboard electrical demand scenarios.

Table 6 details the DC-side and AC-side auxiliary consumers assigned to the variable-load states applied to the 24 V battery-based hybrid system. For each load state, the total imposed demand was obtained by combining the DC contribution with the AC contribution associated with the inverter-fed auxiliary loads. Accordingly, the total load power can be expressed as:

$$P_{\text{load}} = P_{\text{DC}} + P_{\text{AC}} \quad (20)$$

where the DC-side power is calculated as the sum of the individual DC consumers assigned to a given load state:

$$P_{\text{DC}} = \sum P_{\text{DC},i} \quad (21)$$

Table 6. Variable-load-state mapping for the onboard auxiliary consumers listed in Table 5.

Load State	DC Consumers	DC Power [W]	AC Consumers	AC Power [W]	Total Load [W]	Operational Interpretation
LS1-a	AIS transponder; Echosounder; Fixed VHF radio	4 + 3 + 6 = 13	None	0	13	Basic DC navigation state
LS1-b	GPS; portable VHF radio;	15 + 3 = 18	None	0	18	Basic DC navigation state
LS1-c	GPS; portable VHF radio; low-power instrument light	15 + 3 + 1 = 19	None	0	19	Upper LS1 DC-only state
LS2-a	GPS; electronic compass	15 + 1 = 16	AC cabin LED lighting; low-power AC auxiliary socket	20 + 26 = 46	62	Medium load with basic DC navigation and constant inverter-fed demand
LS2-b	GPS; AIS; echosounder; electronic compass; marine instrument	15 + 4 + 3 + 1 + 1 = 24	AC cabin LED lighting; low-power AC auxiliary socket	20 + 26 = 46	70	Medium navigation-monitoring state with AC support load

Table 6. Cont.

Load State	DC Consumers	DC Power [W]	AC Consumers	AC Power [W]	Total Load [W]	Operational Interpretation
LS2-c	GPS; fixed VHF radio; AIS; echosounder; electronic compass	$15 + 6 + 4 + 3 + 1 = 29$	AC cabin LED lighting; low-power AC auxiliary socket	$20 + 26 = 46$	75	Medium navigation-monitoring state with AC support load
LS2-d	GPS; fixed VHF radio; AIS; portable VHF radio; echosounder; electronic compass	$15 + 6 + 4 + 3 + 3 + 1 = 32$	AC cabin LED lighting; low-power AC auxiliary socket	$20 + 26 = 46$	78	Medium recovery state with constant inverter-fed load
LS2-e	GPS; radar; portable VHF radio; electronic compass; marine instrument	$15 + 15 + 3 + 1 + 1 = 35$	AC cabin LED lighting; low-power AC auxiliary socket	$20 + 26 = 46$	81	Upper LS2 state with inverter-fed auxiliary load
LS3-a	GPS; radar	$15 + 15 = 30$	AC cabin LED lighting; auxiliary AC socket; laptop/navigation workstation	$20 + 30 + 65 = 115$	145	High transient load with increased inverter-fed demand
LS3-b	GPS; radar; portable VHF radio; electronic compass; marine instrument	$15 + 15 + 3 + 1 + 1 = 35$	AC cabin LED lighting; auxiliary AC socket; laptop/navigation workstation	$20 + 30 + 65 = 115$	150	Upper high-load transient condition
LS4-a	GPS; fixed VHF radio; AIS; portable VHF radio	$15 + 6 + 4 + 3 = 28$	AC cabin LED lighting; auxiliary AC socket; laptop/workstation; small AC appliance	$20 + 34 + 65 + 65 = 184$	212	Maximum experimental load with high inverter-fed demand
LS4-b	GPS; radar; portable VHF radio; electronic compass; marine instrument	$15 + 15 + 3 + 1 + 1 = 35$	AC cabin LED lighting; auxiliary AC socket; laptop/workstation; small AC appliance	$20 + 34 + 65 + 65 = 184$	219	Maximum load state requiring battery-buffer support
LS4-c	GPS; radar; fixed VHF radio; AIS	$15 + 15 + 6 + 4 = 40$	AC cabin LED lighting; auxiliary AC socket; laptop/workstation; small AC appliance	$20 + 34 + 65 + 65 = 184$	224	Upper experimental load condition

Similarly, the AC-side load is determined from the aggregated power demand of the inverter-fed consumers:

$$P_{AC} = \sum P_{AC,j} \quad (22)$$

When the AC demand is referred to the DC side of the battery system, the inverter conversion efficiency may be explicitly considered as:

$$P_{AC} = \frac{\sum P_{AC,j}}{\eta_{inv}} \quad (23)$$

In the present experimental interpretation, the AC load values reported in Table 6 are expressed at the consumer side, corresponding to the inverter-fed auxiliary loads applied during the measurement campaign. Therefore, the load-state matrix is used as

an operational representation of the imposed DC/AC demand rather than as a detailed loss-separation model of the inverter stage.

For LS1, the absence of AC demand defines DC-only operating conditions, suitable for assessing the capability of the hybrid PV–wind system to cover essential low-power loads and to generate battery-charging surplus. LS2 produces medium auxiliary-load operation by combining DC navigation/communication consumers with AC loads. LS3 and LS4 introduce higher inverter-fed demand levels of 184 W, respectively, allowing the evaluation of battery-buffer support when the imposed load exceeds the instantaneous renewable contribution.

The photovoltaic–wind system investigated in this study is conceived as an auxiliary renewable power generation unit intended to support low-power marine consumers through an experimental architecture based on a 24 V battery DC bus. The proposed configuration is not addressed as the vessel’s primary power supply, but rather as a complementary energy subsystem dedicated to selected loads whose operation depends on the navigation profile, harbour or anchorage conditions, and the instantaneous availability of solar and wind resources.

5.6. Battery Energy-Balance Analysis

During the test performed on 21 September 2025, the hybrid PV–wind system supplied a battery-coupled load network rather than an isolated fixed resistance. The internal DC consumers imposed variable low-power demand on the 24 V bus, while the external AC consumers were applied in discrete inverter-fed steps of 46 W, 115 W, and 184 W. These load states (Table 7) highlight different operating states of a small-vessel auxiliary electrical network and force the hybrid system to operate under changing power-balance conditions.

Table 7. Energy balance under dynamic consumer demand.

Hybrid System P [W]	Load		Total Imposed Load P [W]	Rechargeable Battery Banks		
	DC [W]	AC [W]		V [V]	I [A]	P [W]
31	13	0	13	25.79	0.69	17.79
26	13	0	13	25.78	0.5	12.89
56	19	0	19	26.75	1.4	37.45
93	16	46	62	25.94	1.2	31.128
76	35	46	81	25.31	−0.19	−4.80
58	32	46	78	25.02	−0.8	−20.016
38	29	46	75	24.29	−1.52	−36.92
118	18	0	18	27.79	3.6	100.04
122	30	115	145	25.89	−0.88	−22.78
194	35	115	150	27.79	1.59	44.18
161	40	184	224	25.15	−2.5	−62.87
204	28	184	212	25.58	−0.3	−7.674
166	35	184	219	24.88	−2.12	−52.74
106	24	46	70	25.86	1.39	35.94

The sign of battery power defines the operating mode: $P_{\text{bat}} > 0$ corresponds to charging from surplus WT–PV generation, while $P_{\text{bat}} < 0$ indicates discharging to compensate for the imposed load demand.

The battery bank was therefore the central balancing element of the experimental architecture. Positive battery power indicated that the renewable generation exceeded the active consumer demand and that surplus energy was stored. Negative battery power indicated that the imposed load exceeded the instantaneous renewable generation and that the battery supplied the missing power. The negative battery-power states reported in Table 7 therefore represent transient deficit-compensation regimes rather than supply-failure conditions. For example, in load state LS2-e, the measured hybrid generation was $P_{\text{hyb}} = 76$ W, whereas the imposed load demand was $P_{\text{load}} = 81$ W, resulting in

a battery contribution of $P_{\text{bat}} = -4.80$ W. This operating point shows that instantaneous renewable generation alone cannot guarantee continuous supply when $P_{\text{hyb}}(t) < P_{\text{load}}(t)$. Instead, continuity is maintained only through the coupled action of the WT–PV source, the 24 V/28 Ah AGM VRLA battery bank, the admissible 50% DOD operating window, and the inverter-fed load profile. Consequently, the reported coverage ratios must be interpreted as energy-equivalent feasibility indicators, whereas real-time supply continuity depends on the temporal coincidence between renewable generation, auxiliary-load demand, battery state of charge, and the duration of low-resource intervals.

Because the wind-speed measurement was performed close to the turbine installation area, the WT contribution reported in Table 7 should be interpreted as the effective contribution of the tested vessel-mounted configuration rather than as a generalised turbine power-curve result. The measured inflow velocity $v_1(t)$ may include the effects of local turbulence, flow acceleration or deceleration, and directional distortion induced by the vessel superstructure and by the relative position of the anemometer with respect to the rotor. Consequently, the wind-power contribution $P_{\text{WT}}(t)$ used in the hybrid energy balance is representative of the local experimental inflow conditions associated with the analysed prototype. Its transferability to other vessel geometries, turbine mounting positions, or superstructure layouts therefore requires additional site-specific wind-field characterisation.

Accordingly, the proposed PV–wind system should be interpreted as an auxiliary renewable generation unit connected to a limited-capacity 24 V battery bank, intended to support a selected low-power section of the electrical network of a small vessel. The experimental validation does not claim full-vessel autonomy; it demonstrates the ability of the hybrid source to reduce the net battery discharge and partially supply critical DC and inverter-fed AC loads under variable environmental and load conditions.

Figure 9 shows a representative real-time telemetry dashboard recorded during the experimental measurement campaign of the hybrid WT–PV system. The interface provides simultaneous monitoring of the battery state of charge, DC load demand, AC load demand, and instantaneous hybrid-system power, enabling direct observation of the energy balance within the 24 V DC architecture. At the illustrated operating point, the hybrid system generated 355 W, mainly supplied by the PV subsystem, while the wind-turbine subsystem provided an additional contribution under the existing wind conditions. The dashboard also confirms the concurrent supply of DC and AC consumers, demonstrating the capability of the monitoring platform to capture the operational interaction between renewable generation, storage, inverter operation, and onboard electrical loads.

The correlation between the load profile, hybrid production, and battery energy balance was performed by comparing the instantaneous hybrid power with the simultaneous DC and AC consumer demand. The selected on-board consumers defined the reference daily demand, while the measured production table provided the available renewable power generated by the photovoltaic and wind subsystems. The battery-balance table was then used to identify the operating regime of the storage system: positive battery power indicated surplus renewable generation and battery charging, whereas negative battery power indicated load support from the battery during renewable-generation deficit.

This approach allowed the experimental operation to be interpreted in terms of three energy states: direct load supply, surplus-energy storage, and battery-assisted supply. Consequently, the hybrid system was not evaluated only by its maximum generated power, but by its ability to follow a variable consumer profile representative of low-power maritime applications.

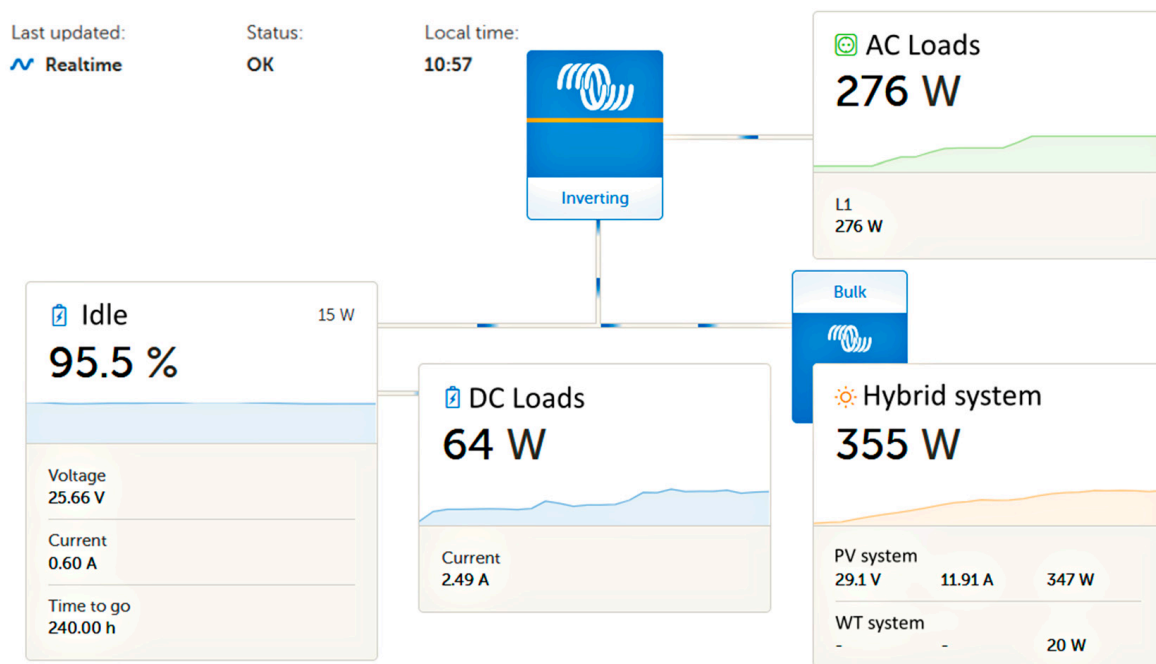


Figure 9. Representative real-time telemetry-dashboard screenshot recorded during the experimental measurement campaign.

5.7. Case Study: Feasibility of Supplying Low-Power Critical Loads on a Small Vessel

The feasibility case study was developed using the experimentally measured active power of the hybrid WT–PV system recorded during the field test performed on 21 September. Unlike a purely nominal sizing approach, the present assessment is based on the real hybrid-system power output P_{real} , measured under variable irradiance, wind-speed, temperature, and incidence-angle conditions. Therefore, the case study provides an energy-based interpretation of the capability of the hybrid renewable subsystem to support selected low-power critical consumers installed on a 5.7 m LOA small marine vessel. The calculation framework considers a daily operating profile consisting of 8 h of navigation and 8 h of stationary operation (Table 8).

The analysed consumers correspond to navigation, communication, and lighting equipment supplied through the 24 V DC battery bus and, where required, through the 24 V DC/230 V AC inverter interface. The considered operating profile consists of 8 h of navigation and 8 h of stationary operation, resulting in a total selected auxiliary-load demand of 599 Wh/day. This load profile represents an operationally relevant critical auxiliary subsystem, not the complete electrical demand of the vessel.

The daily energy demand of the selected consumers is calculated as:

$$E_{\text{load,daily}} = \sum_{i=1}^n P_i t_i \quad (24)$$

For the considered operating profile, the resulting load demand is:

$$E_{\text{load,daily}} = 599 \text{ Wh/day}$$

The average load over the 16 h active operating interval is:

$$P_{\text{avg,16h}} = \frac{E_{\text{load,daily}}}{t_{\text{op}}} = \frac{599}{16} = 37.4 \text{ W} \quad (25)$$

Table 8. Calculation assumption: 8 h navigation/day + 8 h stationary operation/day | System voltage: 230 V AC (via 24 V DC → 230 V AC inverter).

Navigation Equipment	Unit Power (W)	Qty.	Nav. h/Day	Stat. h/Day	Total Energy (Wh/Day)	Remarks
GPS Garmin GPSMAP 923xsv	15	1	8	2	150	Essential
Radar Garmin GMR 18 HD+	15	1	4	0	60	
AIS Transponder Garmin AIS 800	4	1	8	4	48	Active during navigation
Garmin GMC 010-compass	1	1	8	0	8	
Echosounder Lowrance HOOK2-5	3	1	8	0	24	
NASA Marine Clipper	1	1	8	0	8	
Total					298	
Communication Systems						
Standard Horizon GX2200 fixed VHF radio	6	1	8	4	72	Continuous stand-by
Icom IC-M25 portable VHF radio	3	1	2	1	9	Backup
EPIRB McMurdo E5 406 MHz	0.5	1	0	0	0	Emergency only
Total					81	
Lighting Circuits						
LED navigation lights (starboard + port + stern)	10	1	6	0	60	Mandatory at night
LED anchor position light (360°)	5	1	0	8	40	Mandatory at anchor
12 V AC/DC LED strip cabin interior lighting	20	1	2	4	120	Evening/night
Total					220	
TOTAL					599	

The electrochemical storage subsystem consists of a 24 V/28 Ah AGM VRLA battery bank. Its nominal stored energy is:

$$E_{\text{bat,nom}} = V_{\text{bat,nom}} C_{\text{bat,nom}} = 24 \cdot 28 = 672 \text{ Wh} \quad (26)$$

For AGM batteries, full-depth discharge is not a realistic long-term operating condition. Considering a conservative and technically representative depth of discharge of 50%, the usable battery energy becomes:

$$E_{\text{bat,use,50\%}} = DOD \cdot E_{\text{bat,nom}} = 0.50 \cdot 672 = 336 \text{ Wh} \quad (27)$$

The corresponding battery-only autonomy at the average auxiliary-load demand is:

$$t_{\text{bat,use,50\%}} = \frac{E_{\text{bat,use,50\%}}}{P_{\text{avg,16h}}} = \frac{336}{37.4} \approx 9.0 \text{ h} \quad (28)$$

Thus, when a 50% DOD limit is imposed, the battery bank alone can supply approximately 56.1% of the selected 599 Wh/day auxiliary demand:

$$CR_{\text{bat,50\%}} = \frac{E_{\text{bat,use,50\%}}}{E_{\text{load,daily}}} \cdot 100 = \frac{336}{599} \cdot 100 = 56.1\% \quad (29)$$

Consequently, the 24 V/28 Ah battery bank must be interpreted as a short-duration balancing buffer, not as an independent storage unit capable of supplying the complete 16 h load profile without renewable support.

For the experimental case study, the hybrid renewable energy was calculated from the measured active power of the complete WT–PV system. Since the experimental table

contains time-stamped measurements with non-uniform time spacing, the energy was obtained by trapezoidal integration of the real hybrid power P_{real} :

$$E_{\text{hyb,exp}} \approx \sum_{i=1}^{N-1} \frac{P_{\text{real},i} + P_{\text{real},i+1}}{2} \Delta t_i \quad (30)$$

where $P_{\text{real},i}$ is the measured active power of the hybrid WT–PV system at the i -th time-stamp, Δt_i is the time interval between two consecutive measurements, and N is the number of experimental samples.

For the monitored interval on 21 September, corresponding to approximately 8.28 h, the experimentally integrated hybrid energy was:

$$E_{\text{hyb,exp}} \approx 611.3 \text{ Wh} \quad (31)$$

The average experimentally delivered hybrid power over the monitored interval was therefore:

$$P_{\text{hyb,avg}} = \frac{E_{\text{hyb,exp}}}{t_{\text{meas}}} = \frac{611.3}{8.28} \approx 73.8 \text{ W} \quad (32)$$

The renewable coverage ratio of the selected daily auxiliary-load demand is:

$$CR_{\text{RES}} = \frac{E_{\text{hyb,exp}}}{E_{\text{load,daily}}} \cdot 100 = \frac{611.3}{599} \cdot 100 \approx 102.1\% \quad (33)$$

This result shows that, during the experimentally monitored interval, the hybrid WT–PV system generated an amount of energy slightly higher than the daily energy demand of the selected low-power critical consumers. The corresponding energy surplus is:

$$E_{\text{surplus}} = E_{\text{hyb,exp}} - E_{\text{load,daily}} = 611.3 - 599 = 12.3 \text{ Wh} \quad (34)$$

Expressed as an equivalent operating duration at the average selected auxiliary-load demand, the experimentally generated renewable energy corresponds to:

$$t_{\text{load,eq}} = \frac{E_{\text{hyb,exp}}}{P_{\text{avg,16h}}} = \frac{611.3}{37.4} \approx 16.35 \text{ h} \quad (35)$$

Therefore, the measured hybrid renewable production during the analysed day was sufficient, in energy-equivalent terms, to supply the selected low-power critical-load profile for approximately 16.35 h, which is slightly above the defined 16 h daily operating scenario.

When the usable battery energy at 50% DOD is included, the total available energy for the selected auxiliary-load profile becomes:

$$E_{\text{available,50\%}} = E_{\text{hyb,exp}} + E_{\text{bat,use,50\%}} = 611.3 + 336 = 947.3 \text{ Wh} \quad (36)$$

The combined renewable-plus-storage coverage ratio is:

$$CR_{\text{hyb+bat,50\%}} = \frac{E_{\text{available,50\%}}}{E_{\text{load,daily}}} \cdot 100 = \frac{947.3}{599} \cdot 100 \approx 158.1\% \quad (37)$$

The corresponding energy margin is:

$$E_{\text{margin,50\%}} = E_{\text{available,50\%}} - E_{\text{load,daily}} = 947.3 - 599 = 348.3 \text{ Wh} \quad (38)$$

This combined result is more relevant than a battery-only autonomy estimate (Table 9), because it reflects the actual operating principle of the experimental architecture. The

renewable sources directly supply the active consumers whenever sufficient power is available, while the battery compensates the residual mismatch between instantaneous generation and load demand. Thus, the battery is not the primary energy source; it is the power-balancing element of the 24 V DC auxiliary network.

Table 9. Experimental feasibility indicators for supplying selected low-power critical loads.

Indicator	Value/Assumption	Technical Interpretation
Selected daily auxiliary-load demand	599 Wh/day	Energy required by navigation, communication, and lighting consumers
Active operating profile	8 h navigation + 8 h stationary	Reference 16 h daily operating scenario
Average load over active interval	37.4 W	Mean power demand of the selected critical consumers
Battery-bank nominal capacity	24 V/28 Ah	AGM VRLA storage configuration
Battery nominal energy	672 Wh	Full nominal stored energy
Adopted depth of discharge	50% DOD	Conservative operating level for AGM battery cycling
Usable battery energy at 50% DOD	336 Wh	Practical storage energy considered in the case study
Battery-only autonomy at 50% DOD	9.0 h	Battery support without renewable generation
Battery-only coverage at 50% DOD	56.1%	Fraction of daily load covered only by usable storage
Duration of monitored interval	8.28 h	Time base for integrating P_{real}
Experimental hybrid energy	611.3 Wh	Energy obtained from measured real hybrid active power
Average experimental hybrid power	73.8 W	Mean renewable power over the monitored interval
Maximum measured hybrid power	204 W	Peak active power recorded for the complete hybrid system
Minimum measured hybrid power	24 W	Lowest recorded hybrid active power in the table
Renewable coverage ratio	102.1%	Hybrid generation relative to selected daily demand
Renewable energy surplus	12.3 Wh	Difference between measured hybrid energy and selected load demand
Equivalent supplied duration	16.35 h	Duration supported by measured hybrid energy at 37.4 W average load
Renewable + 50% DOD battery energy	947.3 Wh	Combined experimental generation and usable storage
Combined coverage ratio	158.1%	Total available energy relative to selected daily demand
Combined energy margin	348.3 Wh	Remaining energy margin after supplying the selected load profile

The feasibility indicators reported in Table 9 are representative-day case-study metrics derived exclusively from the experimental interval of 21 September 2025 and do not represent average values calculated over the ten-day monitoring campaign. This date was deliberately selected because it corresponded to the lowest-performing and most

unfavourable renewable-generation day recorded during the entire experimental campaign, primarily because of the adverse cloud-cover conditions and the associated limitation of PV production. Accordingly, the analysed interval represents a conservative stress-case assessment rather than a favourable or selectively chosen high-generation scenario. Even under the least favourable conditions observed during the campaign, the experimentally integrated hybrid renewable-energy generation reached $E_{\text{hyb}} = 611.3$ Wh. Relative to the selected daily auxiliary-load demand of $E_{\text{load}} = 599$ Wh/day, this value corresponds to an energy-equivalent renewable coverage ratio of $C_{\text{RES}} = 102.1\%$. When the usable battery reserve associated with a depth of discharge of 50% was included in the energy balance, the combined renewable-plus-storage coverage increased to $C_{\text{hyb+bat}} = 158.1\%$. These results demonstrate the energy-balance feasibility of the coupled WT–PV architecture under the most adverse operating conditions identified throughout the ten-day experimental campaign and confirm that the reported value of $C_{\text{RES}} = 102.1\%$ does not represent a favourable outlier obtained by selecting a high-generation day. Nevertheless, the reported values remain representative-day stress-case indicators and should not be interpreted as ten-day averages or as guaranteed seasonal or annual autonomy metrics.

The small surplus indicates that the system should not be interpreted as a robust full-autonomy solution under all environmental conditions. The feasibility remains dependent on daily irradiance, wind availability, load simultaneity, inverter losses, and the actual state of charge of the battery bank. Therefore, the 50% DOD battery reserve is operationally important. With 336 Wh of usable storage, the battery can compensate transient renewable deficits and extend the energy-equivalent support capability from 16.35 h to approximately:

$$t_{\text{combined},50\%} = \frac{E_{\text{available},50\%}}{P_{\text{avg},16\text{h}}} = \frac{947.3}{37.4} \approx 25.3 \text{ h} \quad (39)$$

This value should be interpreted as an energy-equivalent support duration, not as a guarantee of uninterrupted operation independent of power-flow constraints. It indicates that, for the analysed experimental day, the hybrid WT–PV subsystem and the usable 50% DOD battery reserve provide sufficient energy to support the selected low-power critical consumers with a meaningful operational margin.

From a system-level perspective, the proposed architecture is therefore feasible as an auxiliary renewable-energy supply solution for a 5.7 m LOA small vessel. Its contribution is not the complete replacement of the conventional onboard electrical system, but the reduction in net battery discharge, the extension of operating time for critical low-power consumers, and the improvement of resilience of the 24 V DC auxiliary network. The case study confirms that, under the experimentally measured conditions of 21 September, the hybrid system can support the selected navigation, communication, and lighting load profile when operated together with the 24 V/28 Ah AGM battery bank limited to 50% DOD.

6. Measurement Uncertainty, Data Quantization, and Instrumentation Limitations

6.1. Wind Subsystem Measurement Deviations

During the experimental assessment of the useful electrical power generated by the wind turbine and the corresponding battery-charging power, deviations were observed between the actual computed values and the integer values reported by the smart shunt installed on the negative terminal downstream of the wind controller. The device provides rounded power estimates without decimal resolution, which introduces quantization-related approximation errors in the recorded dataset.

For instance, when the actual turbine output power is 6.43 W, the monitoring device reports both the turbine-generated power and the battery-charging power as 6 W. Conversely, when the actual generated power reaches 6.86 W, the turbine power is still reported as 6 W, whereas the battery-charging power may be displayed as 7 W. This behavior indicates different rounding mechanisms applied internally to the monitored quantities: downward rounding for turbine-side power and nearest-integer rounding for charging power. Consequently, measurement inconsistencies may occur over specific operating intervals, particularly at low power levels where integer quantization becomes proportionally significant.

To mitigate this limitation, the voltage and current values recorded by the same smart shunt were used instead of the directly reported integer power values. Since the charging voltage and current were acquired with higher numerical resolution, the battery-charging power was recalculated as the product of these two variables. This approach enabled a more accurate comparison between experimental and simulated values of the useful electrical power delivered by the wind-energy conversion subsystem.

6.2. Photovoltaic Subsystem Estimation Errors

During the measurements performed on the photovoltaic subsystem, discrepancies were also identified between the power values estimated by the solar charge controller and the values derived from the measured electrical quantities. These deviations originate mainly from the controller-side estimation algorithms, which report power values as integer approximations rather than decimal-resolved measurements.

Such behavior is typical of certain photovoltaic charge controllers that perform discrete voltage and current sampling and subsequently round the calculated power within predefined numerical intervals. As a result, the displayed values of PV-generated power and battery-charging power do not always capture fine variations induced by irradiance fluctuations, temperature changes, or transient operating conditions. This limitation may introduce minor interpretation errors when the controller-reported power values are used directly for experimental validation.

In addition to numerical rounding effects, controller efficiency variations represent another source of discrepancy between the PV input power and the battery-side charging power. Under real operating conditions, the controller receives electrical power from the PV module and delivers an output power that is necessarily lower than, or at most equal to, the input power, depending on the conversion regime. Although the technical documentation specifies a peak efficiency of 98%, this value is not constant across the entire operating range. The instantaneous efficiency may decrease under partial-load conditions, transient irradiance, or non-optimal voltage–current operating points, thereby affecting the measured relationship between generated PV power and effective battery-charging power.

Considering both controller-side estimation errors and realistic efficiency degradation, a conservative efficiency value of 95% was adopted for the analysis of the battery-charging power. Although the nominal peak efficiency is higher, the reduced value provides a more representative approximation of the actual energy-transfer losses occurring under outdoor experimental operation.

The database contains integer-estimated values for the power generated by the wind turbine and photovoltaic module, as well as for the battery-charging power. However, the charging voltage and current were recorded with sufficient numerical resolution, allowing decimal-resolved charging power values to be reconstructed separately for each subsystem.

6.3. Hybrid Subsystem Estimation Errors

In the hybrid WT–PV configuration, the subsystem-level active powers and the aggregated hybrid active power are not necessarily acquired at the same energetic node of the architecture. The PV and wind contributions are monitored on their corresponding source branches, whereas the hybrid power reported by the telemetry platform represents the effective system-level power after interaction with the common 24 V DC bus, the storage interface, the power-conditioning stages, and the inverter-fed load branch. Consequently, the arithmetic sum $P_{PV,real} + P_{WT,real}$ may differ from the monitored value of $P_{hyb,real}$.

A principal source of this deviation is the 24 V DC/230 V AC inverter. In the present experimental interpretation, the AC load values reported in Table 6 refer to the consumer side and are therefore used as an operational representation of the imposed inverter-fed demand, not as a separated inverter-loss model. Since the inverter processes power between the DC bus and the AC auxiliary loads, the DC-side power drawn from the hybrid architecture is higher than the useful AC-side load power because of switching losses, magnetic losses, control-circuit consumption, conductor losses, and thermal dissipation. As the transferred hybrid power increases, the absolute inverter-related losses are also expected to increase, even when the converter operates within its nominal efficiency range.

A conservative efficiency factor of 95% was used to account for conversion and charge-transfer losses in the DC-side energy estimation. Because converter efficiency may decrease under partial-load operation, transient irradiance, and inverter-fed AC demand, the influence of lower aggregate efficiency values is examined in the Section 7 (Discussion) through a 95%/90%/85% sensitivity case. This value should be interpreted as an aggregate operational efficiency of the tested DC charging and energy-transfer path, rather than as the peak efficiency of an individual component. For inverter-fed AC loads, the corresponding DC-side energy demand was therefore considered higher than the nominal useful AC load energy, depending on the inverter efficiency, standby consumption, and operating point.

6.4. Instrumentation-Related Measurement Limitations

The experimental validation process was constrained by the finite metrological performance of the instrumentation chain used for environmental, mechanical, thermal, and electrical data acquisition. Although the selected sensors and acquisition devices were appropriate for outdoor hybrid renewable-energy testing, each measurement channel introduced specific uncertainty components associated with sensor accuracy, resolution, response characteristics, signal conditioning, mounting configuration, and data-acquisition architecture. These limitations are particularly relevant during transient regimes, where rapid variations in irradiance, wind speed, rotor speed, and thermal state may amplify the mismatch between measured and simulated trajectories.

7. Discussion

7.1. Feasibility Interpretation and Comparison with Prior Marine Hybrid Renewable-Energy Studies

The experimental results confirm that the investigated WT–PV architecture should be interpreted as a battery-coupled auxiliary renewable-energy subsystem rather than as a full-vessel autonomous power plant. The system boundary is deliberately restricted to selected low-power auxiliary consumers associated with navigation, communication, lighting, monitoring, and inverter-fed service loads. Under this interpretation, the relevant feasibility indicator is not the instantaneous replacement of the complete onboard electrical network, but the reduction in net battery discharge and the extension of the operating time of the 24 V DC auxiliary bus.

For the representative case study performed on 21 September 2025, the experimentally integrated hybrid renewable energy was $E_{hyb} = 611.3$ Wh over a monitored in-

terval of approximately 8.28 h. Compared with the selected auxiliary-load demand of $E_{\text{load}} = 599 \text{ Wh/day}$, this corresponds to an energy-equivalent renewable coverage ratio of $C_{\text{RES}} = 102.1\%$. When the usable battery reserve corresponding to a 50% depth of discharge (DOD) is included, the available energy increases to $E_{\text{hyb}} + E_{\text{bat},50\% \text{DOD}} = 611.3 + 336 = 947.3 \text{ Wh}$, resulting in a combined renewable-plus-storage coverage ratio of $C_{\text{hyb+bat}} = 158.1\%$. These values indicate that, under the analysed operating conditions, the prototype can support the selected auxiliary-load profile with a measurable energy margin.

Compared with conventional hybrid renewable-energy studies that primarily rely on nominal sizing, simulation-only assessment, or generic load assumptions, the present work contributes through a field-validated marine auxiliary-load framework. The model was parameterized using synchronized experimental inputs, including plane-of-array irradiance S , photovoltaic cell temperature T_c , incidence angle θ , PV-side voltage V_{PV} , wind speed v_1 , and rotor speed n . This provides a stronger validation basis than purely datasheet-driven simulations. Moreover, the feasibility analysis is linked to physically measured hybrid-system power P_{hyb} , rather than only to the theoretical rated capacities of the 395 WPV module and 200 W wind turbine.

The comparison with prior hybrid renewable-energy research should therefore be framed around the level of experimental integration and marine operational specificity. The novelty of the present study is not the isolated use of PV modules, wind turbines, batteries, or MPPT controllers, but the experimentally validated coupling of these subsystems into a small-vessel auxiliary electrical architecture. In this respect, the manuscript extends the prior modelling-oriented literature by connecting WT–PV generation, battery-buffer operation, inverter-fed load states, and representative auxiliary marine demand within a single experimentally monitored framework.

7.2. Marine-Specific Limitations and Applicability

Although the proposed WT–PV prototype is based on components commonly used in low-power off-grid renewable-energy systems, its applicability in the present study is defined by the small-vessel auxiliary-load context, the 24 V DC onboard architecture, and the vessel-mounted experimental configuration. The system is not intended for propulsion supply or full-vessel electrical autonomy, but for reducing the net battery discharge and extending the operating time of selected low-power consumers associated with navigation, communication, lighting, monitoring, and inverter-fed service loads. The operational interpretation therefore differs from a conventional stationary off-grid system, because the hybrid source is assessed against representative vessel operating modes, including navigation and stationary operation corresponding to berthing and anchoring conditions.

The marine installation environment introduces additional uncertainty mechanisms that may affect both the photovoltaic and wind-energy conversion branches. Vessel roll and pitch, heading variation, deck shading, limited installation area, and irradiance reflected from the sea surface may modify the effective incidence angle θ , plane-of-array irradiance S , and photovoltaic cell temperature T_c , thereby influencing the instantaneous PV power contribution $P_{\text{PV}}(t)$. Similarly, variations in apparent wind speed, local turbulence, rotor-position effects, and flow distortion induced by the vessel superstructure may affect the measured inflow velocity $v_1(t)$, rotor speed $n(t)$, and wind-turbine power contribution $P_{\text{WT}}(t)$. Consequently, the hybrid power output $P_{\text{hyb}}(t)$ should be interpreted as the response of the tested vessel-mounted configuration under the measured local environmental forcing rather than as a directly transferable performance map applicable to all small-vessel layouts.

Marine durability factors further define the applicability limits of the present prototype. Salt spray, humidity, thermal cycling, vibration, shock, connector ageing, contact-resistance

variation, and enclosure-sealing degradation may affect long-term electrical reliability, measurement stability, and power-conditioning performance. These degradation mechanisms were not explicitly modelled in the present feasibility assessment, which focused on the synchronized short-term validation of the WT–PV power response and the battery-coupled energy balance. Therefore, extrapolation of the results to extended offshore navigation, severe sea states, or long-term unattended operation requires additional environmental qualification and durability testing.

Within these boundaries, the present dataset is suitable for validating the hybrid mathematical model and assessing the energy-equivalent feasibility of the selected auxiliary-load profile under the tested onboard configuration. However, it should not be interpreted as a complete representation of all navigation, berthing, anchoring, seasonal, sea-state, and installation-layout conditions. Broader generalisation would require extended sea trials covering different vessel headings and speeds, sea states, shading configurations, wind regimes, salt-spray exposure levels, thermal–humidity cycles, and vibration conditions.

7.3. Generalizability of the Representative-Day Stress-Test Case Study

The energy-feasibility results derived from 21 September 2025 must be interpreted as a representative stress-test case study rather than as a universal guarantee of autonomy. This day was deliberately selected because it imposed unfavorable operating conditions on the hybrid WT–PV system, particularly through reduced photovoltaic availability caused by high cloud cover and non-uniform irradiance. Under these conditions, the PV subsystem, which represents the dominant renewable contributor in the proposed architecture, operated below its favorable clear-sky potential. The wind-energy conversion subsystem provided a variable and intermittent contribution, but this contribution was not treated as a favorable replacement for the reduced PV output. Instead, the selected interval was used to assess whether the battery-coupled hybrid system could preserve auxiliary-load feasibility under a constrained and dynamically variable generation scenario.

The resulting renewable-energy coverage ratio of $C_{RES} = 102.1\%$ must therefore be interpreted as a stress-case energy-equivalent result. The experimentally integrated hybrid production, $E_{hyb} = 611.3$ Wh, slightly exceeded the selected auxiliary-load demand, $E_{load} = 599$ Wh/day, despite the reduced PV resource and variable WT contribution. This supports the technical feasibility of the proposed auxiliary power architecture under the analysed unfavourable day. However, the result does not imply guaranteed uninterrupted power supply under all possible temporal combinations of renewable generation and load demand. Continuous supply depends on the instantaneous balance between $P_{hyb}(t)$, $P_{load}(t)$, the battery state of charge, inverter-fed demand, the DOD constraint, and the duration of low-resource intervals.

This distinction is important because the coverage ratio is an integrated daily energy indicator rather than a deterministic real-time autonomy indicator. A daily value above 100% indicates that the total renewable energy produced during the monitored interval was sufficient, in energy-equivalent terms, to cover the selected auxiliary-load profile. It does not guarantee that $P_{hyb}(t) \geq P_{load}(t)$ at every timestamp. The negative battery-power states reported in the load-balance analysis confirm this behaviour: during specific operating intervals, the battery supplied the residual deficit when instantaneous renewable generation was lower than the active DC/AC load demand. Therefore, the battery bank is not an optional reserve in this architecture, but the required balancing element that converts intermittent WT–PV production into usable auxiliary-load support.

Although the 21 September 2025 case study provides a conservative, cloud-adverse validation of the proposed auxiliary WT–PV architecture within the September monitoring campaign, its results should not be extrapolated to winter operation or to prolonged

low-resource sequences. Under January–February conditions, the lower solar altitude, shorter daylight duration, persistent cloud cover, precipitation, and reduced plane-of-array irradiance may substantially decrease E_{PV} and, consequently, E_{hyb} . Under such conditions, the renewable-only coverage ratio $C_{RES} = E_{hyb}/E_{load}$ may fall below the value of 102.1% obtained for the analysed representative-day case study, particularly when the useful wind contribution is also limited.

The installed battery bank was not sized to support two or three consecutive days characterised by low irradiance and insufficient wind contribution. The experimental storage subsystem has a nominal energy capacity of $E_{bat,nom} = 24 \times 28 = 672$ Wh, of which $E_{bat,50\%DOD} = 336$ Wh is considered usable under the adopted 50% depth-of-discharge constraint. By comparison, supplying the selected auxiliary-load profile of $E_{load} = 599$ Wh/day for two and three consecutive low-resource days would require approximately 1198 Wh and 1797 Wh of usable stored energy, respectively. Under the same 50% DOD limit, the corresponding nominal storage capacities would be approximately 2396 Wh and 3594 Wh, representing values approximately 3.6 and 5.3 times greater than the nominal capacity of the installed experimental battery bank. Therefore, multi-day autonomy under winter conditions or during prolonged low-resource sequences remains outside the experimentally validated scope of the present prototype and would require dedicated storage sizing and a multi-season experimental assessment.

7.4. Sensitivity to Battery Depth of Discharge, Battery Derating, and Inverter Efficiency

The combined coverage ratio is sensitive to the assumed usable battery energy. The installed battery bank has a nominal configuration of 24 V/28 Ah, corresponding to a nominal stored energy of $E_{bat,nom} = 672$ Wh. For AGM VRLA batteries, full-depth discharge is not appropriate for long-term operation; therefore, a 50% depth-of-discharge (DOD) limit was adopted as a practical compromise between usable energy and cycle-life preservation. At 50% DOD, the usable battery reserve is $E_{bat} = 336$ Wh.

It should be explicitly acknowledged that the installed storage subsystem was not sized through a preliminary energy-balance analysis or an optimisation procedure based on the vessel auxiliary-load profile. Its nominal capacity was instead dictated by the limited hardware resources available for the experimental campaign and should therefore be regarded as a constraint of the test platform rather than as an optimised storage-design solution.

A simple DOD sensitivity analysis shows the dependence of the combined coverage indicator on the selected discharge window. At 30%, 50%, and 80% DOD, the usable battery reserves become 201.6 Wh, 336 Wh, and 537.6 Wh, respectively. When combined with the measured representative-day renewable energy $E_{hyb} = 611.3$ Wh, the total available energy becomes 812.9 Wh, 947.3 Wh, and 1148.9 Wh. Relative to the selected auxiliary demand $E_{load} = 599$ Wh/day, the corresponding combined coverage ratios are approximately 135.7%, 158.1%, and 191.8%. Thus, the 158.1% value is not an intrinsic system constant, but a DOD-dependent feasibility indicator.

The battery-energy estimate may also be optimistic because Peukert effects, temperature-dependent capacity derating, ageing, internal-resistance evolution, and charge-acceptance limitations were not explicitly included in the present model. If these second-order effects reduce the usable 50% DOD reserve by 10–25%, the effective battery reserve decreases from 336 Wh to approximately 302–252 Wh. Under this conservative derating envelope, the combined renewable-plus-storage energy remains approximately 913–863 Wh, corresponding to 152.4–144.1% of the selected 599 Wh/day auxiliary demand. This confirms that the feasibility indication remains positive for the analysed day, but the operational margin is reduced.

The inverter and charge-transfer efficiency also affect the renewable-only coverage result. Using the measured representative-day renewable energy of 611.3 Wh as the reference, a reduction of the aggregate conversion efficiency from 95% to 90% or 85% would decrease the effective renewable energy to approximately 579.1 Wh and 546.9 Wh, respectively. The renewable-only coverage would therefore decrease from 102.1% to approximately 96.7% and 91.3%. However, when the 50% DOD battery reserve is included, the combined coverage remains approximately 152.8% and 147.4%, respectively. This demonstrates that the renewable-only margin is sensitive to conversion losses, while the battery-coupled architecture provides a more resilient energy-equivalent support margin.

7.5. Continuous-Supply Implications of Negative Battery-Power States

The negative battery-power values reported for certain load states do not invalidate the feasibility assessment; rather, they identify the operating intervals in which the storage subsystem is required to preserve the power balance. In Table 7, LS2-e provides a representative example: the measured hybrid generation was $P_{\text{hyb}} = 76 \text{ W}$, while the simultaneous load demand was $P_{\text{load}} = 81 \text{ W}$, resulting in a battery power of $P_{\text{bat}} = -4.80 \text{ W}$. The small difference between the nominal 5 W deficit and the measured battery contribution of -4.80 W is consistent with the finite numerical resolution of the monitoring chain and with the fact that the measured quantities are acquired at different energetic nodes of the DC-bus architecture.

This result demonstrates that continuous supply cannot be inferred solely from the condition $E_{\text{hyb}} \geq E_{\text{load}}$. The energy balance, $E_{\text{hyb}} = 611.3 \text{ Wh}$ and $E_{\text{load}} = 599 \text{ Wh/day}$, confirms daily energy-equivalent feasibility for the representative stress-test day, but uninterrupted operation additionally requires short-term power deficits to be absorbed by the battery within the allowable DOD range. Therefore, the system should be interpreted as a battery-coupled auxiliary supply architecture in which the WT–PV subsystem reduces net battery discharge and extends operating time, while the battery bank compensates for unfavourable load–generation coincidence whenever $P_{\text{hyb}}(t) < P_{\text{load}}(t)$.

7.6. Future Research

The above limitations define the principal directions required to extend the present feasibility assessment. Future experimental work should include multi-season monitoring campaigns capable of capturing winter-solstice irradiance minima, prolonged cloud-cover intervals, and variations in the prevailing wind regime. Battery modelling should also be extended beyond the present DOD-based usable-energy approximation by incorporating Peukert effects, temperature-dependent derating, ageing mechanisms, internal-resistance evolution, charge-acceptance constraints, and state-of-health degradation. In addition, a full-vessel energy audit is required to contextualise the selected auxiliary-load demand of $E_{\text{load}} = 599 \text{ Wh/day}$ relative to the total onboard electrical-energy demand. Finally, future studies should implement a formal sensitivity and uncertainty framework addressing the adopted DOD limit, inverter efficiency, local wind-inflow bias, turbulence effects, PV shading, and load simultaneity.

8. Conclusions

This study developed, implemented, and experimentally validated a low-power hybrid wind–photovoltaic energy system intended to support selected auxiliary electrical consumers of a 5.7 m LOA small marine vessel. The proposed architecture integrates a 395 W photovoltaic module, a 200 W wind turbine, a 24 V DC battery-coupled distribution bus, a 24 V DC/230 V AC inverter interface, and a 24 V/28 Ah AGM VRLA battery bank. The system was not designed as a propulsion-energy source or as a full-vessel autonomous

power plant, but as a supplementary renewable-energy subsystem dedicated to navigation, communication, lighting, monitoring, and other low-power auxiliary loads. The result should not be generalized to full-vessel autonomy or propulsion loads.

The experimental and numerical results confirmed that the developed model provides a high-fidelity representation of the real hybrid WT–PV power response under variable environmental and operating conditions. The simulation framework was parameterized using field-acquired inputs rather than only nominal manufacturer data, including wind speed, rotor speed, plane-of-array irradiance, PV cell temperature, solar-incidence angle, and experimentally measured PV-side voltage. The point-by-point comparison between simulated and measured hybrid active power demonstrated very low deviation levels, with a mean error of -0.1041 W, a mean absolute error of 0.3988 W, a root mean square error of 0.4931 W, and a mean absolute percentage error of 0.5946% . These values indicate negligible systematic bias, limited dispersion of the residuals, and strong predictive consistency across the analysed operating range.

The experimental validation also showed that the hybrid system can reproduce the dynamic behaviour of the renewable sources under non-uniform atmospheric forcing. The PV subsystem provided the dominant contribution during intervals with favourable irradiance, whereas the wind subsystem supplied additional short-term power contributions during wind-speed excursions. This complementarity is particularly relevant for small-vessel auxiliary electrical networks, where the instantaneous demand is moderate but continuity of supply depends on the ability of the system to compensate the temporal mismatch between generation and consumption.

The auxiliary-load assessment was based on a representative daily operating profile consisting of 8 h of navigation and 8 h of stationary operation. The selected low-power critical consumers produced a total energy demand of 599 Wh/day, corresponding to an average active-period demand of 37.4 W over the 16 h reference interval. This load profile included navigation, communication, and lighting equipment and was therefore representative of a restricted but operationally relevant auxiliary subsystem, rather than of the complete onboard electrical demand of the vessel.

The 24 V/28 Ah AGM VRLA battery bank provided a nominal stored energy of 672 Wh. However, the analysis showed that this value must not be interpreted as practical full-depth autonomy. When a technically conservative 50% depth of discharge is considered, the usable battery energy decreases to 336 Wh, corresponding to approximately 9.0 h of battery-only operation at the average load of 37.4 W. In this configuration, the battery alone covers approximately 56.1% of the 599 Wh/day selected auxiliary demand. Therefore, the battery bank must be interpreted as a short-duration balancing buffer, not as a stand-alone energy source capable of reliably supplying the complete 16 h reference load profile without renewable support.

A more conclusive feasibility result was obtained by integrating the experimentally measured real active power of the complete hybrid WT–PV system. Over the monitored interval of approximately 8.28 h, the hybrid system generated 611.3 Wh, with an average experimental hybrid power of 73.8 W. The measured hybrid power varied between 24 W and 204 W, demonstrating that the system operated over a wide range of renewable-generation states. The integrated hybrid energy exceeded the 599 Wh/day selected auxiliary demand by 12.3 Wh, corresponding to a renewable coverage ratio of 102.1%. Expressed as an equivalent supply duration at the average selected load demand, the measured renewable energy corresponds to approximately 16.35 h, slightly exceeding the 16 h daily operating scenario considered in the case study.

When the usable 50% DOD battery reserve is included together with the experimentally measured renewable production, the available energy increases to 947.3 Wh. This

corresponds to a combined renewable-plus-storage coverage ratio of 158.1% and an energy margin of 348.3 Wh relative to the selected daily auxiliary demand. The corresponding energy-equivalent support duration is approximately 25.3 h at the 37.4 W average load. This value should not be interpreted as guaranteed uninterrupted autonomy under all operating conditions, but it provides a quantified indication that the hybrid WT–PV sub-system and the 24 V/28 Ah battery bank, operated within a 50% DOD limit, can support the selected low-power critical loads with a meaningful energy margin under the analysed experimental conditions.

The load-state analysis further confirmed that the proposed system is suitable for variable auxiliary-load operation. DC-only load states are appropriate for assessing direct low-power supply and battery-charging surplus, whereas inverter-fed AC load states impose higher demand levels and require battery-buffer support. The use of discrete AC load states of 46 W, 115 W, and 184 W enabled the assessment of the 24 V DC/230 V AC conversion stage under representative small-vessel auxiliary demand conditions. The results showed that the hybrid system should be interpreted as a battery-coupled auxiliary generation unit: renewable sources directly supply the active loads when available, while the battery compensates the residual deficit during unfavourable generation intervals.

Overall, the study demonstrates that a compact hybrid WT–PV architecture can provide a technically viable supplementary power source for selected low-power auxiliary consumers on a small marine vessel. The main contribution of the system is not the complete replacement of conventional onboard generation, but the reduction in net battery discharge, the extension of auxiliary-load operating time, and the improvement of resilience of the 24 V DC onboard electrical network. Under the analysed experimental conditions, the system generated sufficient renewable energy to cover the selected 599 Wh/day critical-load profile and, when combined with the 50% DOD battery reserve, provided a quantified operational margin.

Author Contributions: Conceptualization, C.P. and A.D.D.; methodology, P.P. and A.P.; software, C.P. and I.C.; validation, F.D., G.S. and A.R.B.; formal analysis, I.C. and N.O.V.; investigation, D.C. and A.D.D.; writing—original draft preparation, C.P. and F.D.; writing—review and editing, I.C., A.R.B. and P.P.; supervision, F.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: This research was carried out at the Romanian Naval Academy “Mircea cel Bătrân”, whose support is acknowledged. The authors would also like to thank the reviewers for their constructive feedback and valuable suggestions.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

LOA	Length Overall
WECS	Wind-Energy Conversion System
PV	Photovoltaic
MPPT	Maximum power point tracking
ECS	Energy conversion system
RES	Renewable-energy system
RTD	Resistance thermometer detector
DAQ	Data acquisition

SoC	State of charge
ARE	Absolute Relative Error
DC	Direct current
AC	Alternating current
AGM	Absorbent Glass Mat
DC-AC	Direct-current to alternating-current conversion
GPS	Global Positioning System
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
MAE	Mean absolute error
MAPE	Mean absolute percentage error
MPP	Maximum power point
PMSG	Permanent-magnet synchronous generator
POA	Plane-of-array
PV-ECS	Photovoltaic energy conversion system
RMSE	Root mean square error
TSR	Tip-speed ratio
VE.Direct	Victron Energy Direct communication interface
VHF	Very high frequency
VRLA	Valve-regulated lead-acid
WT	Wind turbine
DOD	Depth of discharge

Symbols

A	Wind-turbine swept area [m^2]
C_p	Wind-turbine power coefficient [-]
E	Energy [Wh] or [kWh]
f	Frequency signal from pulse-count acquisition [Hz]
I	Terminal/output PV current [A]
I_D	Diode current [A]
I_L	Photocurrent/light-generated current [A]
I_{PV}	PV-side output current [A]
I_{RS}	Reverse saturation current term [A]
I_{sc}	Short-circuit current [A]
I_{sh}	Shunt/leakage current [A]
n	Rotor rotational speed [rpm]
N_p	Number of parallel-connected PV strings [-]
N_s	Number of series-connected PV modules/cells [-]
P	Electrical active power [W]
P_{AC}	AC-side load power [W]
P_{bat}	Battery power; positive for charging, negative for discharging [W]
P_{DC}	DC-side load power [W]
P_{hyb}	Total hybrid WT-PV power [W]
P_m	Mechanical power extracted by the wind turbine [W]
P_{PV}	Photovoltaic electrical power [W]
P_{real}	Experimentally measured power [W]
P_{sim}	Simulated power [W]
P_{WT}	Wind-turbine electrical power [W]
R	Wind-turbine rotor radius [m]
R_S	PV series resistance [Ω]
R_{sh}	PV shunt resistance [Ω]
S	Plane-of-array solar irradiance [W/m^2]
T	PV cell/module temperature [$^{\circ}\text{C}$] or [K], depending on equation
T_{ref}	Reference cell temperature [K]
t	Time [s], [min], or [h]

V	Terminal voltage [V]
V_{oc}	Open-circuit voltage [V]
V_{PV}	PV-side terminal voltage [V]
V_T	Thermal voltage [V]
v_1	Incident wind speed at the wind-turbine inlet [m/s]
x_1-x_6	Empirical coefficients of the wind-turbine power-coefficient equation [-]
Alb	Ground-reflection/albedo coefficient [-]
Greek letters	
β	Wind-turbine blade-pitch angle [°]
η	Generic efficiency [-]
η_{aux}	Auxiliary-circuit/wind-controller electronics efficiency [-]
η_e	Electrical generator conversion efficiency [-]
η_{inv}	Inverter efficiency [-]
η_m	Mechanical drivetrain efficiency [-]
η_{MPPT}	MPPT charge-controller efficiency [-]
θ	Incidence angle of solar radiation on the tilted PV plane [°]
λ	Tip-speed ratio [-]
ρ	Air density [kg/m ³]
ω	Rotor angular speed [rad/s]

References

- Calà, F.; Tarchi, P.; Frassinetti, L.; Gursesli, M.C.; Guazzini, A.; Lanata, A. Expectancy Violation: Climate Change Associations May Reveal Underlying Brain-Evoked Responses of Implicit Attitudes. In *2024 46th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*; IEEE: Piscataway, NJ, USA, 2024. [\[CrossRef\]](#)
- Elias, M.A.; Yi, L.X.; Jamaludin, A. Potential of Onshore Wind Energy in Malaysia: A Brief Study on Wind Conditions. In *2024 IEEE Sustainable Power and Energy Conference (iSPEC)*; IEEE: Piscataway, NJ, USA, 2024. [\[CrossRef\]](#)
- Qian, X. Renewable energy development in the Arab countries in the context of energy transition. In *2025 4th International Symposium on New Energy Technology Innovation and Low Carbon Development (NET-LC)*; IEEE: Piscataway, NJ, USA, 2025; pp. 231–234. [\[CrossRef\]](#)
- Zereshkian, S.; Mansoury, D. Solar-wind hybrid energy system to supply electricity for offshore oil and gas platforms in the Caspian Sea: A case study. *J. Eng.* **2023**, 2023, e12239. [\[CrossRef\]](#)
- Musa-Basheer, H.O.; Eyiomika Salami, M.J. Robustness analysis of Airborne Wind Energy Systems Using Neurofuzzy Control Approach. In *2024 IEEE 5th International Conference on Electro-Computing Technologies for Humanity (NIGERCON)*; IEEE: Piscataway, NJ, USA, 2024. [\[CrossRef\]](#)
- Harrouz, A.; Belatrache, D.; Boulal, K.; Colak, I.; Kayisli, K. Social Acceptance of Renewable Energy dedicated to Electric Production. In *2020 9th International Conference on Renewable Energy Research and Application (ICRERA)*; IEEE: Piscataway, NJ, USA, 2020; pp. 283–288. [\[CrossRef\]](#)
- Lamia, N.A.; Zerin, N.S.; Biswas, O.; Khan, T.R. A Study on Public Awareness and Perception of Renewable Energy Policies in Bangladesh among Young Citizens. In *2024 7th International Conference on Development in Renewable Energy Technology (ICDRET)*; IEEE: Piscataway, NJ, USA, 2024. [\[CrossRef\]](#)
- Ji, R.; Zhang, H.; Yu, W.; Liu, M.; Qiu, Z.; Li, S. Wind Speed Correction Method for Wind Power Based on Markov Chains. In *2024 IEEE 5th International Conference on Advanced Electrical and Energy Systems (AEES)*; IEEE: Piscataway, NJ, USA, 2024; pp. 441–446. [\[CrossRef\]](#)
- Rodriguez, J.L.D.; Khalil, A.; Ouchani, F.Z.; Ghennioui, A. Multidimensional Analysis of Renewable Energy Development Opportunities in the MENA Region. In *2025 15th International Renewable Energy Congress (IREC)*; IEEE: Piscataway, NJ, USA, 2025. [\[CrossRef\]](#)
- Kasaeian, A.; Zarkhah, N.; Akhond Dezfouli, P.; Samankan, S.; Yan, W.M. A review of the applications of solar photovoltaic in marine vessels and ships. *Appl. Energy* **2025**, 396, 126178. [\[CrossRef\]](#)
- Pan, P.; Sun, Y.; Yuan, C.; Yan, X.; Tang, X. Research progress on ship power systems integrated with new energy sources: A review. *Renew. Sustain. Energy Rev.* **2021**, 144, 111048. [\[CrossRef\]](#)
- Zhu, J.; Chen, L. Stochastic Optimization of Onboard Photovoltaic Hybrid Power System Considering Environmental Uncertainties. *J. Mar. Sci. Eng.* **2024**, 12, 1240. [\[CrossRef\]](#)
- Zhang, Q.; Bao, C.; Han, P. Towards intelligent energy management in hybrid ships: Predicting and optimizing solar, wind, and diesel energy. *Ocean Eng.* **2025**, 339, 122092. [\[CrossRef\]](#)

14. Iqbal, R.; Liu, Y.; Zeng, Y.; Zhang, Q.; Zeeshan, M. Comparative study based on techno-economics analysis of different shipboard microgrid systems comprising PV/wind/fuel cell/battery/diesel generator with two battery technologies: A step toward green maritime transportation. *Renew. Energy* **2024**, *221*, 119670. [\[CrossRef\]](#)
15. Huang, M.; He, W.; Incecik, A.; Cichon, A.; Królczyk, G.; Li, Z. Renewable energy storage and sustainable design of hybrid energy powered ships: A case study. *J. Energy Storage* **2021**, *43*, 103266. [\[CrossRef\]](#)
16. Bouhounta, A.; Moulahoum, S.; Kabache, N. Hybrid backup energy based on PV/Wind system for marine tugboat: A case study of ASD tug of Arzew port in Algeria. *Wind Eng.* **2022**, *46*, 1343–1358. [\[CrossRef\]](#)
17. Ara, S.R.; Paul, S.; Rather, Z.H. Two-level planning approach to analyze techno-economic feasibility of hybrid offshore wind-solar pv power plants. *Sustain. Energy Technol. Assess.* **2021**, *47*, 101509. [\[CrossRef\]](#)
18. Huang, J.; Iglesias, G. Hybrid offshore wind–solar energy farms: A novel approach through retrofitting. *Energy Convers. Manag.* **2024**, *319*, 118903. [\[CrossRef\]](#)
19. Luhaniwal, J.; Puppala, H.; Agarwal, S.; Mathur, T. Framework for strategic deployment of hybrid offshore solar and wind power plants: A case study of India. *J. Clean. Prod.* **2024**, *479*, 144009. [\[CrossRef\]](#)
20. Molotov, P.; Vaskov, A.; Tyagunov, M. Modeling Processes in Microgrids with Renewable Energy Sources. In *2018 International Ural Conference on Green Energy (UralCon)*; IEEE: Piscataway, NJ, USA, 2018; pp. 203–208. [\[CrossRef\]](#)
21. Xing, C.; Xi, X.; He, X.; Liu, M. Research on the MPPT Control Simulation of Wind and Photovoltaic Complementary Power Generation System. In *2020 IEEE Sustainable Power and Energy Conference (isPEC)*; IEEE: Piscataway, NJ, USA, 2020; pp. 1058–1063. [\[CrossRef\]](#)
22. Wasonga, A.; Saulo, M.; Odhiambo, V. Solar-Wind Hybrid Energy System for New Engineering Complex- Technical University of Mombasa. *Int. J. Energy Power Eng.* **2014**, *4*, 73–80. [\[CrossRef\]](#)
23. Wang, G.; Zhang, J.; Zhang, W.; Liu, H.; Cui, X. Research on Transient Stability Analysis of Wind-Photovoltaic-Thermal-bundled Power Transmitted System. In *2021 IEEE 5th Conference on Energy Internet and Energy System Integration (EI2)*; IEEE: Piscataway, NJ, USA, 2021; pp. 366–370. [\[CrossRef\]](#)
24. Chaudhary, V.; Bhargava, A.; Bhasin, S. Modeling and Simulation of grid connected hybrid power system integrated with solar PV/Wind and controlled by Voltage Regulator. In *2019 International Conference on Communication and Electronics Systems (ICCES)*; IEEE: Piscataway, NJ, USA, 2019; pp. 1316–1320. [\[CrossRef\]](#)
25. Allani, M.Y.; Jomaa, M.; Mezghani, D.; Mami, A. Modelling and simulation of the hybrid system PV-wind with MATLAB/SIMULINK. In *2018 9th International Renewable Energy Congress (IREC)*; IEEE: Piscataway, NJ, USA, 2018; pp. 1–6. [\[CrossRef\]](#)
26. Redhwi, I.; Almalki, S.; Radhwi, H.; Jarwali, A.; Abaaltahin, A.; Fallatah, A. Advancements in battery technology: A comprehensive review. *Clean Energy Sci. Technol.* **2026**, *4*, 573. [\[CrossRef\]](#)
27. Hoarca, C.I.; Enescu, F.M. On the energy efficiency of standalone fuel cell/renewable hybrid power sources Part II: Simulation results for variable load profile with different renewable energy sources profiles (RES). In *2018 International Conference on Applied and Theoretical Electricity (ICATE)*; IEEE: Piscataway, NJ, USA, 2018. [\[CrossRef\]](#)
28. Buchatskiy, P.Y.; Onishchenko, S.V.; Teploukhov, S.V.; Kuzmin, K.A. Modeling of Wind Generator in the Power Supply System of an Individual Consumer Using SimInTech. In *2024 8th International Conference on Information, Control, and Communication Technologies (ICCT)*; IEEE: Piscataway, NJ, USA, 2024. [\[CrossRef\]](#)
29. Ye, H.; Tang, W.; Li, Z.; Li, S.; Chen, Y.; Yang, Y. Risk Assessment Method for Renewable Energy Uncertainty Considering Energy Storage and Automatic Generation Control. In *2024 IEEE 8th Conference on Energy Internet and Energy System Integration (EI2)*; IEEE: Piscataway, NJ, USA, 2024; pp. 2583–2587. [\[CrossRef\]](#)
30. Ben Ali, R.; Aridhi, E.; Mami, A. Design, modeling and simulation of hybrid power system (Photovoltaic-WIND). In *2016 17th International Conference on Sciences and Techniques of Automatic Control and Computer Engineering (STA)*; IEEE: Piscataway, NJ, USA, 2017; pp. 461–467. [\[CrossRef\]](#)
31. Rao, T.E.; Elango, S.; Swamy, G.G. Power management strategy between pv-wind-fuel hybrid system. In *2021 7th International Conference on Electrical Energy Systems (ICEES)*; IEEE: Piscataway, NJ, USA, 2021; pp. 101–107. [\[CrossRef\]](#)
32. Ahmed, N.A.; Miyatake, M. A Stand-Alone Hybrid Generation System Combining Solar Photovoltaic and Wind Turbine with Simple Maximum Power Point Tracking Control. In *2006 CES/IEEE 5th International Power Electronics and Motion Control Conference*; IEEE: Piscataway, NJ, USA, 2009; pp. 1–7. [\[CrossRef\]](#)
33. Anoune, K.; Bouya, M.; Ghazouani, M.; Astito, A.; Ben Abdellah, A. Hybrid renewable energy system to maximize the electrical power production. In *2016 International Renewable and Sustainable Energy Conference (IRSEC)*; IEEE: Piscataway, NJ, USA, 2017; pp. 533–539. [\[CrossRef\]](#)
34. ISO 9060:2018; Solar Energy—Specification and Classification of Instruments for Measuring Hemispherical Solar and Direct Solar Radiation. ISO: Geneva, Switzerland, 2018.
35. 03101-L: Wind Sentry Anemometer. Available online: <https://www.campbellsci.asia/03101-sentry-anemometer> (accessed on 28 May 2026).

36. ROS Remote Optical LED Sensor—Monarch Instrument. Available online: <https://monarchinstrument.com/product/ros-remote-optical-led-sensor/> (accessed on 28 May 2026).
37. ABB. *Technical Application Papers No.13 Wind Power Plants*; ABB: Bergamo, Italy, 2011; 136p. Available online: <https://library.e.abb.com/public/92faf0c1913f5651c1257937002f88e8/1SDC007112G0201.pdf> (accessed on 29 May 2026).
38. Sarkar, R.; Julai, S.; Tong, C.W.; Chao, O.Z.; Rahman, M. Mathematical modelling and simulation of induction generator based wind turbine in MATLAB/SIMULINK. *ARPJ J. Eng. Appl. Sci.* **2015**, *10*, 17276–17280.
39. Kulkarni, H.; Kulkarni, A.; Pagire, T.; Magdum, S. Mathematical Modeling, Installation of Wind turbine and its analysis in MATLAB. In *2022 International Conference on Electronics and Renewable Systems (ICEARS)*; IEEE: Piscataway, NJ, USA, 2022; pp. 142–149. [[CrossRef](#)]
40. Yin, Y.; Liao, M.; Lyu, P. The dynamic stability analysis of wind turbines under different control strategies. In *2015 5th International Conference on Electric Utility Deregulation and Restructuring and Power Technologies (DRPT)*; IEEE: Piscataway, NJ, USA, 2016; pp. 2581–2586. [[CrossRef](#)]
41. Deliu, F.; Popa, C.; Ciocoi, I.; Popov, P.; Deliu, A.D.; Bordianu, A.; Cazacu, E. Fixed-Gain and Adaptive Pitch Control for Constant-Speed, Constant-Power Operation of a Horizontal-Axis Wind Turbine. *Energies* **2026**, *19*, 394. [[CrossRef](#)]
42. Photovoltaic Plants Cutting Edge Technology. From Sun to Socket. Available online: <https://search.abb.com/library/Download.aspx?DocumentID=9AKK107492A3277&LanguageCode=en&DocumentPartId&Action=Launch> (accessed on 31 May 2026).
43. Rawan, A.; Yasin, N.M.; Alshamaa, A.N.K. Design and Simulation of a Grid Tied Single Phase SPWM Inverter Using Matlab. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *745*, 012009. [[CrossRef](#)]
44. Ramos-hernanz, J.; Lopez-guede, J.M.; Zulueta, E. Reverse Saturation Current Analysis in Photovoltaic Cell Models. *WSEAS Trans. Power Syst.* **2017**, *12*, 231–237.
45. Modi, S. Mathematical Modeling, Simulation and Performance Analysis of Solar Cell. In *2018 International Conference on Power Energy, Environment and Intelligent Control (PEEIC)*; IEEE: Piscataway, NJ, USA, 2018; pp. 730–734.
46. Huynh, D.C.; Dunnigan, M.W. Unknown Parameter Estimation of a Detailed Solar PV Cell Model. In *2020 IEEE REGION 10 CONFERENCE (TENCON)*; IEEE: Piscataway, NJ, USA, 2020. [[CrossRef](#)]
47. Popa, C.; Deliu, F.; Popa, A.; Volintiru, N.O.; Deliu, A.D.; Ciocoi, I.; Popov, P. Traceable Time-Domain Photovoltaic Module Modeling with Plane-of-Array Irradiance and Solar Geometry Coupling: White-Box Simulink Implementation and Experimental Validation. *Energies* **2026**, *19*, 1437. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.