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Hybrid PV–VAWT Automatic Fish Feeding System for Sustainable Aquaculture

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Abstract

This study developed and experimentally evaluated an automatic fish feeding system powered by a hybrid photovoltaic (PV)–Vertical Axis Wind Turbine (VAWT) energy architecture for small-scale aquaculture applications. The prototype integrated PV generation, a VAWT, battery storage, charge control, a DC–AC inverter, a programmable timer, and an auger-based feeding mechanism. An engineering Design and Development approach was applied through prototype design, assembly, laboratory testing, and field evaluation. VAWT performance was evaluated under controlled laboratory conditions and at two field environments, Lubuk Bakung and Tanjung Api-Api Port, while PV performance was assessed with and without the feeder load. The two automatic feeder units required a combined electrical power of 52 W. The PV subsystem produced a maximum of 76.85 W without feeder load and 60.80 W under feeder load, providing an 8.80-W (16.9%) instantaneous margin above feeder demand at peak output. VAWT maximum power reached 17.304 W in the laboratory, 17.93 W at Tanjung Api-Api, and 0.689 W at Lubuk Bakung, demonstrating substantial site-dependent variation in wind-energy contribution. Battery input voltage remained within 12.4–12.6 V during the Lubuk Bakung observations, while the inverter supplied 208–218 V AC under the tested light-load condition. The feeding mechanism completed the observed programmed cycles without mechanical interruption or pellet blockage. Overall, the findings demonstrate the technical feasibility of a PV-dominant, VAWT-supplemented, battery-buffered architecture for autonomous automatic fish feeding under the tested conditions.

Keywords: Automatic Fish Feeder; Battery Energy Storage; Hybrid Renewable Energy; Photovoltaic; Sustainable Aquaculture; Vertical Axis Wind Turbine

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INTRODUCTION

Aquaculture has become an increasingly important component of global aquatic food production, food security, and rural economic development. The Food and Agriculture Organization of the United Nations reported that aquaculture surpassed capture fisheries in aquatic-animal production in 2022, emphasizing the growing role of aquaculture in future food systems (Food and Agriculture Organization of the United Nations [FAO], 2024). Feed management is central to this production system because feeding frequency, timing, and amount influence fish growth, feed utilization, production cost, and water quality (El Shal et al., 2021; Chiu et al., 2022). Feed availability and management are also persistent constraints in smallholder aquaculture systems (Johnson et al., 2025).

Many small-scale aquaculture operations still depend substantially on manual feeding. Manual practice can produce irregular feeding schedules, variable feed delivery, increased labor requirements, and avoidable feed losses when feeding is not adequately controlled (Handoko Putra et al., 2023). Automated feeders provide a practical alternative by delivering feed according to programmed schedules and reducing dependence on continuous operator intervention (El Shal et al., 2021; Al-Rajhi et al., 2023; Rahayu et al., 2026). Recent smart-aquaculture studies further show how sensing, predictive modeling, and intelligent control can support more systematic farm management (Guo et al., 2022; Chiu et al., 2022; Ubina et al., 2023; Abdullah et al., 2024).

Automation, however, creates a corresponding requirement for dependable electrical power. This requirement can constrain deployment in rural or off-grid aquaculture locations where electricity access is limited or unreliable. Distributed solar and wind technologies are relevant alternatives for such applications, particularly when combined with storage and power-management components (Khojim et al., 2023; Fikako et al., 2023). Because both solar and wind resources vary with environmental conditions, hybrid renewable-energy systems can reduce dependence on a single source and provide a more flexible source-to-storage architecture (Zaqiyah et al., 2024; Gajewski & Pieńkowski, 2021; Falope et al., 2024).

For the present application, PV generation was configured as the dominant daytime source, while a VAWT was incorporated as a supplementary source when usable wind energy was available. This arrangement is consistent with hybrid PV–wind–battery architectures in which storage buffers temporal mismatches between renewable generation and electrical demand (Das et al., 2021; Gajewski & Pieńkowski, 2021). Small-scale VAWTs are attractive for distributed applications because of their compact configuration and ability to operate with changing wind direction, although their output remains sensitive to site conditions, turbine geometry, and operating state (Kouloumpis et al., 2020; Santamaría et al., 2022; Wei et al., 2021; Ramaini et al., 2023; Karjadi, 2024). Comparative Indonesian studies also show that the electrical contribution of PV and VAWT technologies is strongly conditioned by solar irradiance and wind availability (Nurpulaela et al., 2023).

Previous studies therefore provide strong foundations for the individual elements of the proposed system but reveal an integration gap. Automatic-feeding studies have primarily emphasized feeder mechanics, scheduling, sensing, or control (El Shal et al., 2021; Chiu et al., 2022; Handoko Putra et al., 2023; Al-Rajhi et al., 2023; Rahayu et al., 2026). Renewable-energy studies have investigated hybrid PV–wind systems, VAWT performance, and energy management (Das et al., 2021; Santamaría et al., 2022; Wei et al., 2021; Falope et al., 2024). Aquaculture-related renewable-energy work has also demonstrated hybrid PV–wind power for pond equipment such as shrimp-pond aeration (Khojim et al., 2023). Comparatively less attention has been given to a prototype in which PV generation, VAWT generation, storage, power conditioning, programmed control, and automatic feed dispensing operate as one integrated off-grid system.

Table 1 summarizes the distinction between representative prior studies and the present work. The novelty of this study lies primarily in system-level integration rather than in introducing a new PV technology, VAWT concept, or feeder mechanism individually.

Table 1. Comparison of Previous Studies and Research Gap

Reference	Research focus	PV	VAWT/ wind	Hybrid/ storage	Automatic feeding	Gap relative to the present study
El Shal et al. (2021)	Automatic fish feeder design and testing	✗	✗	✗	✓	Feeder performance without hybrid renewable-energy integration.
Chiu et al. (2022)	AIoT precision feeding management	✗	✗	✗	✓	Precision feeding and control without autonomous renewable-energy supply.
Das et al. (2021)	PV/wind/diesel /battery hybrid system	✓	✓	✓	✗	Hybrid-energy design without an automatic aquaculture feeder.
Santamaría et al. (2022)	VAWT prototype characterization	✗	✓	✗	✗	Focused on turbine performance.
Wei et al. (2021)	Full-scale VAWT wake characterization	✗	✓	✗	✗	Focused on VAWT flow behavior.
Khojim et al. (2023)	Hybrid PV–wind system for shrimp-pond aeration	✓	✓	✓	✗	Applied hybrid energy to aeration rather than automatic feeding.
Falope et al. (2024)	Hybrid-energy integration and management	✓	✓	✓	✗	Review and energy-management focus without fish-feeder prototype.
This study	Integrated PV–VAWT-powered automatic fish feeding prototype	✓	✓	✓	✓	Integrates renewable generation, storage, power conditioning, control, and feed dispensing with laboratory and field testing.

Based on this research gap, the study hypothesized that a PV-dominant, VAWT-supplemented, battery-buffered architecture could provide the electrical conditions required to operate the automatic fish-feeding prototype under the tested conditions. Specifically, PV generation was expected to satisfy feeder demand during favorable daytime solar conditions, whereas stored energy and supplementary wind generation would support the architecture when instantaneous PV output was insufficient.

Accordingly, this study aimed to design, construct, and experimentally evaluate an automatic fish feeding system powered by a hybrid PV–VAWT architecture. The specific objectives were to characterize PV electrical performance with and without the feeder load; evaluate VAWT electrical performance under controlled laboratory conditions and natural field environments at Lubuk Bakung and Tanjung Api-Api; assess battery-voltage and inverter-output behavior; determine renewable-power adequacy relative to the 52-W feeder requirement; and verify functional operation of the timer-controlled auger feeding mechanism.

METHOD

Research Design and Experimental Settings

This study used an engineering Design and Development approach comprising requirement identification, system design, prototype fabrication and integration, experimental testing, and descriptive quantitative evaluation. The staged workflow allowed the renewable-generation, storage, power-conditioning, and automatic-feeding subsystems to be examined individually and as an integrated prototype.

Experiments were conducted in three testing environments. Controlled VAWT testing was performed at the Electrical Engineering Laboratory of Politeknik Negeri Sriwijaya using a blower as the artificial wind source, consistent with established small-scale VAWT laboratory-testing practice (Ahmed et al., 2020; Wekesa et al., 2020). Field evaluation of the PV subsystem, integrated feeder, battery, and VAWT was conducted in the Lubuk Bakung area of Siring Agung Urban Village, Ilir Barat I District, Palembang City, South Sumatra, Indonesia. An additional VAWT field test was conducted at Tanjung Api-Api Port, South Sumatra, to evaluate electrical-power performance under a different natural operating environment.

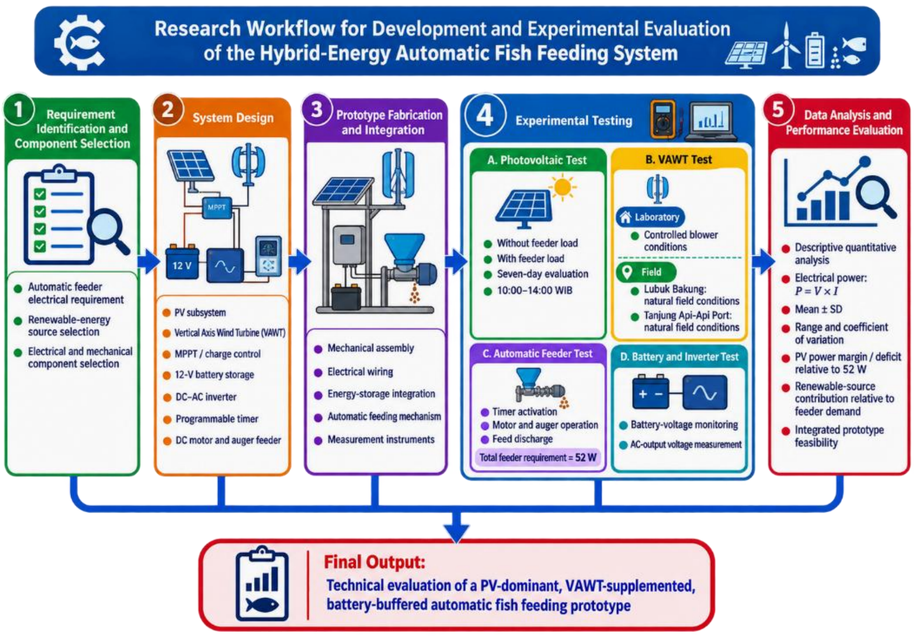

Figure 1. Research workflow for the design, development, experimental testing, and performance evaluation of the hybrid-energy automatic fish feeding system.

Prototype Development

Hybrid Renewable-Energy System

The hybrid renewable-energy subsystem combined PV and VAWT generation with battery storage and power-conditioning components. PV generation served as the primary daytime electrical source, while the VAWT provided supplementary generation when usable wind energy was available. This configuration follows the general architecture of hybrid PV–wind–battery systems in which multiple renewable sources are coordinated through storage and power-management stages (Gajewski & Pieńkowski, 2021).

The PV charging path incorporated a Maximum Power Point Tracking (MPPT) charge controller to regulate battery charging. MPPT is used in PV systems to maintain operation near the available maximum-power point as environmental conditions vary (Esram & Chapman, 2007). The battery supplied stored electrical energy through the inverter and feeder-control circuit. Figure 2 shows the electrical wiring used to integrate the renewable-energy sources, charge-control stage, storage, inverter, and feeder.

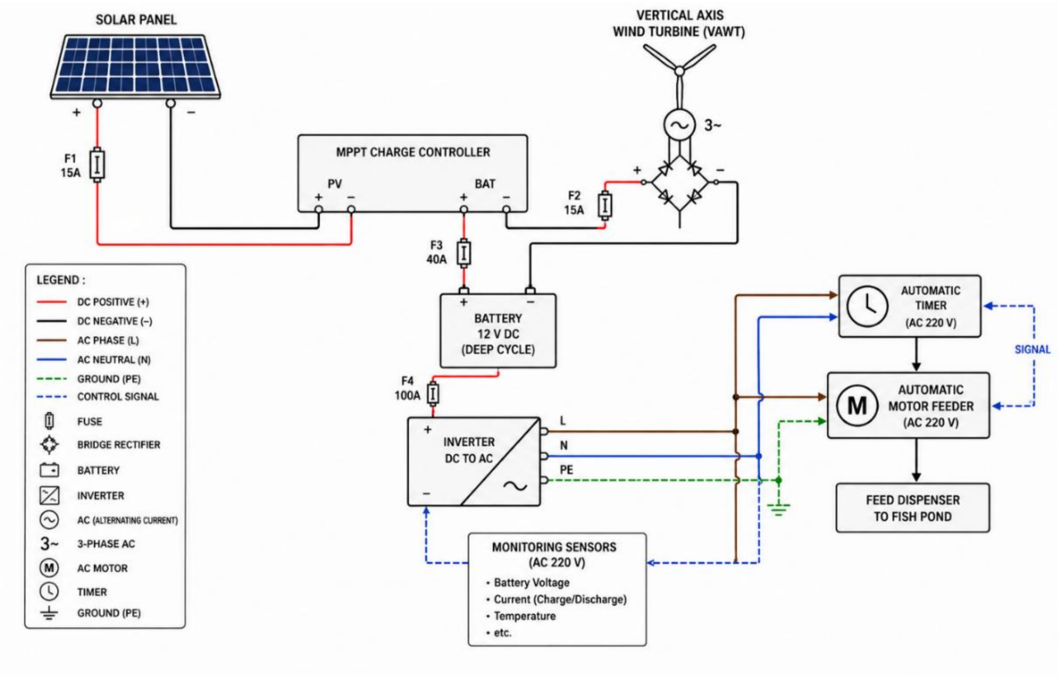

Figure 2. Electrical Wiring Diagram of the Hybrid Renewable Energy System

Automatic Fish Feeding System

The automatic feeding subsystem consisted of a feed hopper, auger-based dispensing mechanism, DC motor, programmable digital timer, and electrical control circuit. Fish pellets were stored in the hopper above the auger. At the preset feeding time, the timer energized the motor circuit, causing the DC motor to rotate the auger and transport pellets toward the outlet. When the programmed operating interval ended, the timer disconnected the motor circuit and stopped dispensing. Timer-controlled, motor-driven dispensing is consistent with established automatic-feeder designs used in aquaculture (El Shal et al., 2021; Rahayu et al., 2026).

Prototype evaluation focused on functional timer activation, motor and auger operation, pellet discharge, observed blockage, electrical power demand, and the ability of the energy subsystem to support the tested feeding cycles. Quantitative feed-mass uniformity was not used as a performance endpoint because replicated gravimetric feed-discharge measurements were not conducted.

Figure 3. Physical Prototype of the Developed Automatic Fish Feeding System

Measured and Controlled Variables

Environmental input variables included solar radiation intensity (W/m²) for PV testing and wind speed (m/s) for VAWT testing. Electrical response variables included output voltage (V), output current (A), calculated electrical power (W), battery input voltage (V), and inverter AC-output voltage (V). VAWT testing additionally included turbine rotational speed (RPM). Operational variables for the feeder included timer activation, auger rotation, feed discharge, observed pellet blockage, and the feeder electrical-power requirement.

The principal hardware configuration was maintained within the relevant comparative tests, including the PV panel, VAWT, charge-control system, 12-V battery, inverter, timer configuration, feeder mechanism, and electrical connections. Overall hybrid-system efficiency was not treated as an experimental response variable because a complete set of simultaneous source-input and load-output energy measurements was not available.

Components, Instrumentation, and System Specifications

The principal system components and measurement instruments are summarized in Table 2. Nominal component ratings describe the hardware configuration and were not used as substitutes for measured experimental performance.

Table 2. Components and Specifications of the Developed Prototype

Component	Specification	Function
Photovoltaic (PV) panel	50 Wp nominal specification	Primary renewable-energy source
Vertical Axis Wind Turbine (VAWT)	200–300 W nominal specification	Supplementary renewable-energy source
MPPT charge controller	12/24 V	Regulates PV battery charging
Battery	12 V, 20 Ah deep-cycle	Electrical-energy storage
DC–AC inverter	220 VAC nominal output	Power conditioning for AC-side loads/control
Automatic timer	Programmable digital timer	Controls feeder operating schedule
Feed-drive assembly	DC motor with auger mechanism	Transfers pellets from hopper to outlet
Current/voltage sensor	INA219	Electrical voltage and current monitoring
Control/data hardware	Arduino/ESP8266 platform	Measurement and prototype-control support
Anemometer	Digital wind-speed measurement	Measures wind speed during VAWT testing
Solar power meter	Digital solar-radiation measurement	Measures incident solar radiation
Digital multimeter	Voltage/current measurement	Verification of electrical measurements

Prototype Assembly Procedure

Assembly was conducted sequentially to ensure mechanical stability and correct electrical integration. First, supporting structures for the PV panel, VAWT, battery compartment, and automatic feeder were fabricated. The PV panel was installed at an inclination of approximately 10–15° according to the prototype design, while the VAWT was mounted on its supporting pole. The renewable-energy sources were then connected to the charge-control and battery-storage stage according to Figure 2. The battery was connected to the DC–AC inverter and feeder-control circuit.

The feeding subsystem was assembled by coupling the hopper, auger shaft, DC motor, timer, and outlet. Measurement instruments were then installed or positioned to record solar radiation, wind speed, electrical voltage, current, turbine RPM, battery voltage, and inverter output where applicable. Before testing, electrical connections, mechanical fasteners, support structures, timer operation, and auger rotation were inspected.

Experimental Procedure

Prototype evaluation comprised four complementary test stages: PV testing, VAWT laboratory and field testing, automatic feeder functional testing, and battery/inverter electrical testing.

Solar Photovoltaic Performance Test

The PV subsystem was evaluated over seven consecutive days under two operating conditions: without feeder load and with the automatic feeder load connected. The term "without feeder load" was used to distinguish the baseline condition from operation with the two feeder units connected. Measurements were conducted between 10:00 and 14:00 WIB. Solar radiation intensity, voltage, current, calculated electrical power, and battery voltage were recorded according to the available observation intervals.

During feeder-load testing, the two automatic feeder units represented a combined electrical requirement of approximately 52 W. Measured PV power was compared with this 52-W threshold to determine whether instantaneous PV generation was above or below feeder demand at the reported observation times.

Vertical Axis Wind Turbine Performance Test

VAWT performance was evaluated under one controlled laboratory condition and two natural field environments. In the laboratory, a blower supplied artificial wind. Five sequential observations were collected between 15:00 and 15:40 WIB at 10-min intervals. Blower voltage was varied from 130 to 200 V to establish different airflow conditions, and wind speed was measured experimentally. Wind speed, turbine RPM, generator voltage, current, and electrical power were recorded at each observation. Controlled and field-based testing are widely used to characterize small VAWT operating behavior (Ahmed et al., 2020; Santamaría et al., 2022; Pietrykowski et al., 2023).

Natural-wind testing at Lubuk Bakung used the same five observation times. Wind speed, turbine RPM, output voltage, current, electrical power, and battery input voltage were recorded. An additional field test at Tanjung Api-Api Port recorded VAWT electrical power at 15:00, 15:10, 15:20, 15:30, and 15:40 WIB for comparison with laboratory and Lubuk Bakung power output.

Automatic Fish Feeding System Test

The automatic feeder was evaluated while connected to the hybrid power system. During each test cycle, the programmed timer initiated feeder operation, the DC motor rotated the auger, and pellets were discharged from the hopper. At the end of the programmed interval, the timer stopped the motor and terminated the feeding cycle. Functional evaluation considered completion of the programmed cycle, motor and auger operation, pellet discharge, observed blockage, electrical-power demand, and the availability of electrical support from the PV–battery–VAWT architecture.

Battery and Inverter Electrical Test

Battery-side voltage was monitored during the Lubuk Bakung VAWT field test at the same five observation times used for the wind measurements. These observations were used to characterize short-duration voltage variation and were not used to estimate complete state of charge, usable capacity, or battery autonomy.

The DC–AC inverter was evaluated separately under light-load conditions using small electrical devices, including a mobile-phone charger rated at 5 V, 1 A and a 10-W lamp. AC-output voltage was measured during load operation and compared with the nominal 220-V output level. The test evaluated voltage adequacy; it did not provide the complete DC-input and AC-output power measurements required to determine inverter efficiency.

Performance Indicators and Calculations

Electrical power generated by the PV and VAWT subsystems was calculated from measured voltage and current using Equation (1).

$$P = V \times I \quad (1)$$

where P is electrical power (W), V is measured voltage (V), and I is measured current (A).

Instantaneous PV power margin relative to the two-feeder demand was calculated using Equation (2).

$$M = P_{PV} - P_{load} \quad (2)$$

where M is the instantaneous margin or deficit (W), P_PV is measured PV power (W), and P_load is the 52-W feeder requirement. Positive M indicates a surplus relative to instantaneous feeder demand; negative M indicates a deficit requiring support from stored energy.

The relative contribution of a measured source output to feeder demand was calculated using Equation (3).

$$C = (P_{source} / P_{load}) \times 100 \quad (3)$$

Descriptive means, sample standard deviations, coefficients of variation, and inverter-voltage deviation were calculated using Equations (4)–(7).

$$\bar{x} = (1/n)\, \Sigma\, x_i \quad (4)$$

$$s = \sqrt{[\Sigma(x_i - \bar{x})^2 / (n - 1)]} \quad (5)$$

$$CV = (s / \bar{x}) \times 100 \quad (6)$$

$$\Delta V = [(V_{measured} - V_{nominal}) / V_{nominal}] \times 100 \quad (7)$$

Maximum values obtained under different experimental conditions were not summed to estimate simultaneous hybrid-system output.

Data Analysis

Experimental data were analyzed using descriptive quantitative methods. PV performance was evaluated by comparing output with and without the feeder load and by comparing reported loaded PV power with the 52-W instantaneous feeder requirement. VAWT performance was evaluated separately for laboratory, Lubuk Bakung, and Tanjung Api-Api conditions. Cross-environment comparison focused on electrical power as the common final performance variable.

Means, sample standard deviations, ranges, coefficients of variation, power margins, and relative source contributions were calculated only where supported by the available measurements. Because the VAWT and battery datasets were short sequential observation series rather than independent experimental replicates, statistical summaries were interpreted descriptively and no inferential significance testing was applied. Battery performance was characterized from the short-duration voltage profile, inverter performance from the measured AC-output range, and feeder performance from successful timer activation, auger operation, feed discharge, observed blockage, and completion of the tested feeding cycles.

RESULTS AND DISCUSSION

Prototype Development and Functional Integration

The hybrid-energy automatic fish feeding prototype was successfully assembled and functionally integrated as a single system incorporating renewable-energy generation, storage, power conditioning, and automatic feed dispensing. The developed system comprised PV generation, a VAWT, charge control, a 12-V battery, a DC–AC inverter, a programmable timer, a DC motor, a feed hopper, and an auger-based dispensing mechanism. Figure 4 presents the overall prototype configuration.

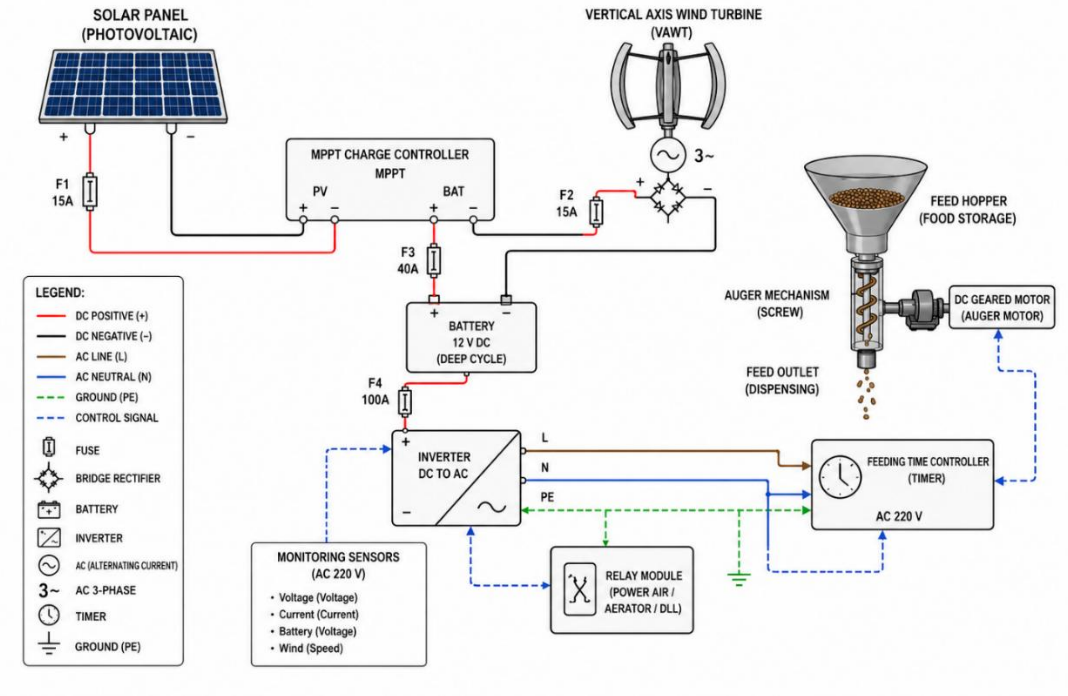

Figure 4. Overall Prototype of the Hybrid Energy Automatic Fish Feeding System

Automatic Fish Feeding Performance

The automatic feeding subsystem consisted of a programmable timer, DC motor, feed hopper, and auger-based dispensing mechanism (Figure 5). During the observed feeding cycles, the timer activated the motor according to the preset schedule, causing the auger to rotate and transfer pellets from the hopper to the outlet. At the end of the programmed interval, the timer disconnected the motor circuit and stopped auger rotation.

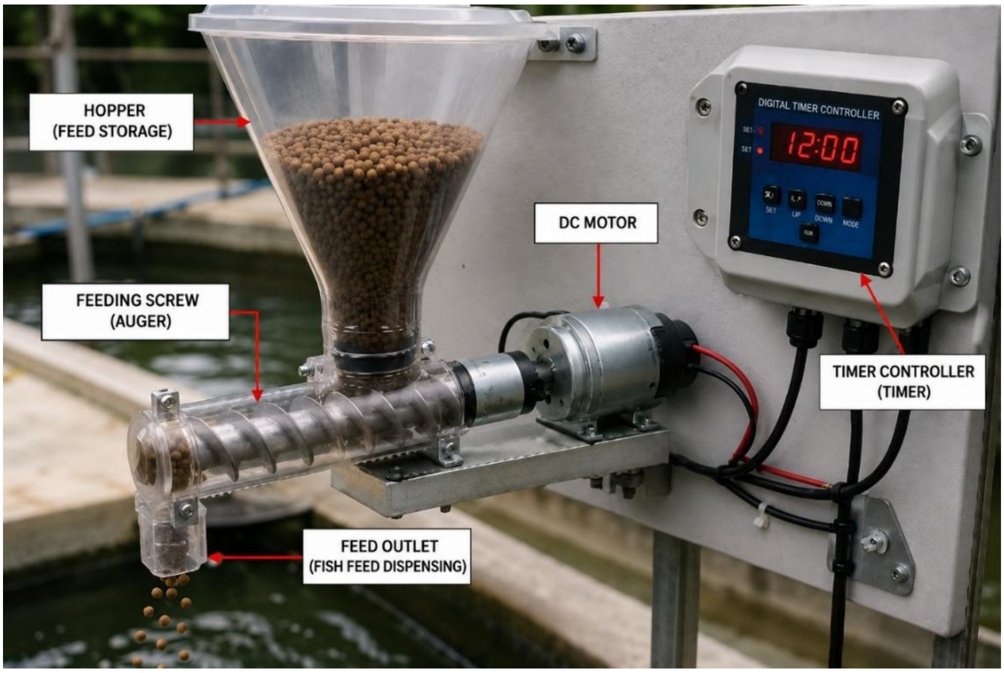

Figure 5. Automatic Fish Feeding Mechanism

The feeder completed the observed operating cycles without mechanical interruption. No pellet blockage was observed within the hopper or auger during the test period, and feed was consistently discharged through the outlet during feeder activation. The combined electrical demand of the two feeder units was approximately 52 W.

Figure 6 presents the energy pathway from renewable generation through charge control and storage to the automatic feeding load. Functional testing confirmed that the generation, storage, power-conditioning, timer-control, and feed-dispensing components could operate as an integrated prototype.

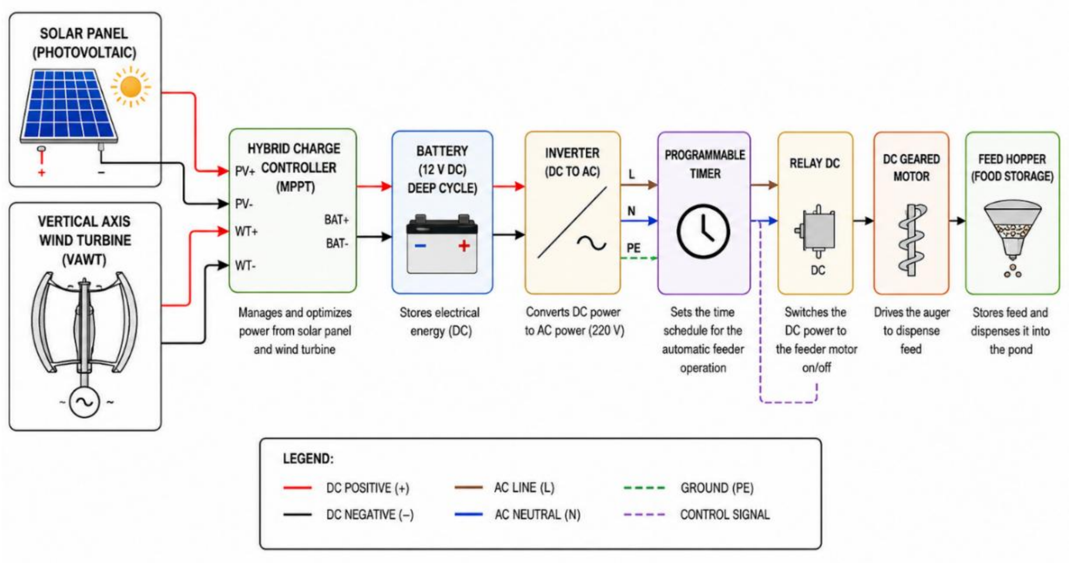

Figure 6. Energy Flow of the Hybrid Renewable Energy Automatic Fish Feeding System

Photovoltaic Performance

Performance without Feeder Load

The PV subsystem was evaluated over seven consecutive days to characterize daytime electrical output. Without the feeder load, the highest reported output was 76.85 W, recorded on the third day at approximately 12:00 WIB. The highest output values were generally observed around 11:00–12:00 WIB, while lower values occurred later in the afternoon. These observations established the baseline PV performance before the feeder demand was introduced.

Performance under Feeder Load

Under feeder-load conditions, the maximum reported PV output reached 60.80 W at 12:00 WIB. Relative to the 52-W requirement of the two feeder units, this value provided an instantaneous power margin of 8.80 W, equivalent to 16.9% above feeder demand.

PV output subsequently decreased to 46.20 W at 13:00 WIB and 41.75 W at 14:00 WIB. These values corresponded to instantaneous deficits of 5.80 W (11.2%) and 10.25 W (19.7%), respectively, relative to the 52-W feeder demand. Figure 7 summarizes the reported loaded-PV values relative to the feeder threshold.

The maximum value of 76.85 W without feeder load and the maximum value of 60.80 W under feeder load represent different operating conditions and were therefore interpreted separately.

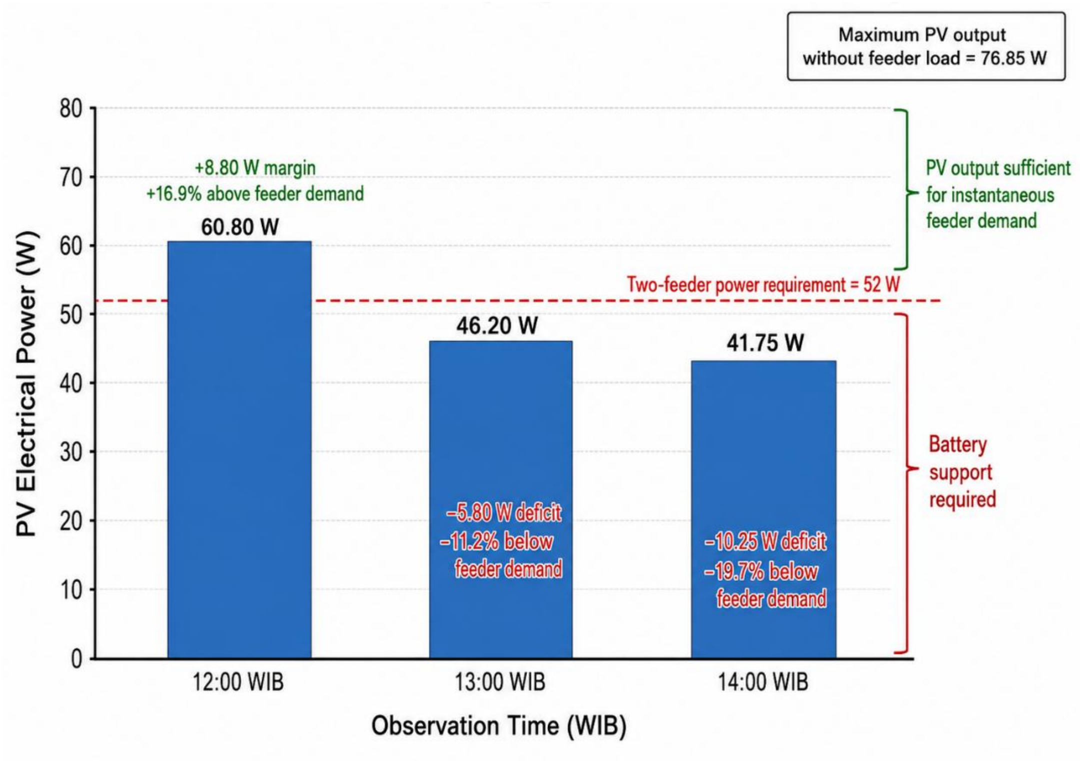

Figure 7. Photovoltaic electrical power under feeder load relative to the 52-W automatic feeder requirement.

VAWT Performance under Laboratory and Field Conditions

Laboratory Performance

Laboratory testing used a blower to characterize VAWT operation under controlled artificial-wind conditions. Measured wind speed ranged from 4.412 to 9.358 m/s across the five observations. Table 3 presents the complete laboratory measurements.

Table 3. Laboratory VAWT Test Results

Time	Wind speed (m/s)	Turbine RPM	Voltage (V)	Current (A)	Power (W)	Blower voltage
15:00	4.412	111	38.0	0.35	13.300	130
15:10	5.719	146	46.0	0.25	11.500	150
15:20	8.442	437	56.6	0.24	13.584	170
15:30	8.855	161	29.7	0.38	11.286	190
15:40	9.358	163	41.2	0.42	17.304	200

As shown in Table 3, electrical power ranged from 11.286 to 17.304 W, with a descriptive mean of 13.395 ± 2.417 W across the five sequential observations. The highest laboratory power output, 17.304 W, was recorded at 15:40 WIB at a measured wind speed of 9.358 m/s. RPM, voltage, current, and power showed point-to-point variation across the applied test conditions.

Lubuk Bakung Field Performance

Field testing at Lubuk Bakung was conducted under natural wind conditions. Five measurements were recorded at 10-min intervals between 15:00 and 15:40 WIB. Table 4 presents wind speed, turbine RPM, voltage, current, electrical power, and battery input voltage.

Table 4. VAWT Field Test Results in Lubuk Bakung

Time	Wind speed (m/s)	Turbine RPM	Voltage (V)	Current (A)	Power (W)	Battery input voltage (V)
15:00	4.320	275	4.30	0.12	0.5160	12.4
15:10	4.489	292	5.10	0.13	0.6630	12.4
15:20	5.508	317	5.30	0.13	0.6890	12.5
15:30	5.369	331	5.15	0.11	0.5665	12.5
15:40	5.373	325	5.22	0.12	0.6264	12.6

As summarized in Table 4, wind speed ranged from 4.320 to 5.508 m/s. Electrical power ranged from 0.5160 to 0.6890 W, with a descriptive mean of 0.612 ± 0.071 W. The maximum field output of 0.689 W occurred at 15:20 WIB, when the measured wind speed was 5.508 m/s, output voltage was 5.30 V, and current was 0.13 A. Battery input voltage remained within 12.4–12.6 V.

Tanjung Api-Api Field Performance and Comparative Electrical Power

The VAWT was also evaluated at Tanjung Api-Api Port. Measured electrical-power values were 13.81, 12.15, 14.28, 11.85, and 17.93 W at 15:00, 15:10, 15:20, 15:30, and 15:40 WIB, respectively. These measurements yielded a descriptive mean of 14.00 ± 2.43 W, with the maximum value of 17.93 W recorded at 15:40 WIB.

Figure 8 compares the electrical-power profiles obtained under laboratory conditions and at the two field locations. The laboratory profile ranged from 11.286 to 17.304 W, the Tanjung Api-Api profile from 11.85 to 17.93 W, and the Lubuk Bakung profile from 0.5160 to 0.6890 W.

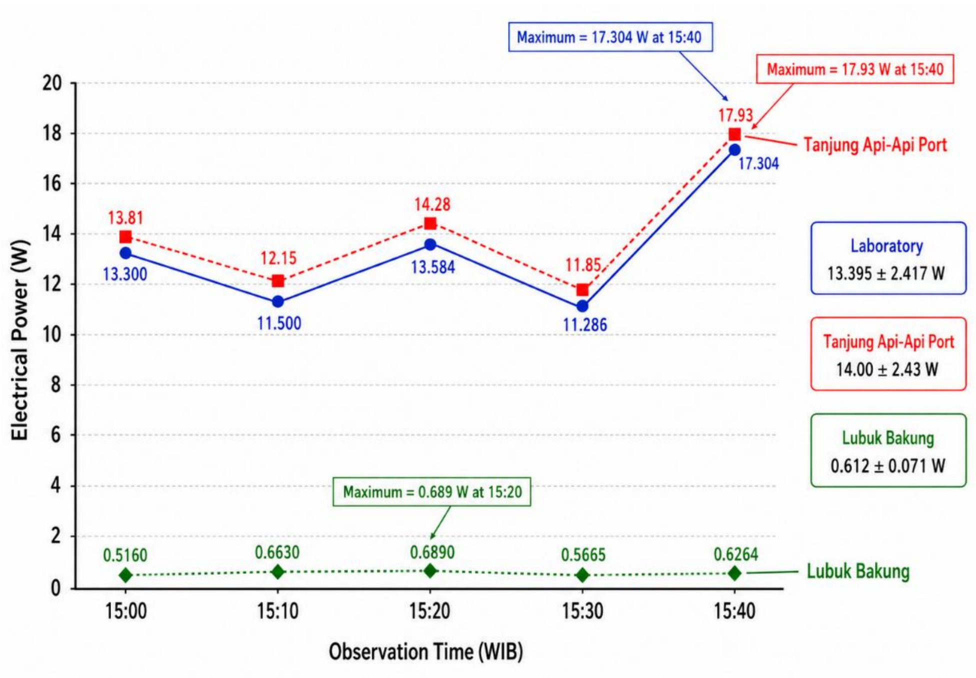

Figure 8. VAWT electrical-power output under laboratory and field test conditions.

Integrated Hybrid-System Power Adequacy

Table 5 summarizes the principal electrical and operational results of the integrated prototype. Quantitative results include PV and VAWT output, battery input voltage, inverter output, and total feeder demand; operational observations describe timer activation, auger operation, feed discharge, and completion of the tested feeding cycles.

Table 5. Overall Performance of the Hybrid Renewable-Energy Automatic Fish Feeding System

Performance parameter	Experimental result
Maximum PV output without feeder load	76.85 W
Maximum PV output under feeder load	60.80 W
VAWT maximum output, laboratory	17.304 W
VAWT maximum output, Tanjung Api-Api	17.93 W
VAWT maximum output, Lubuk Bakung	0.689 W
Battery input voltage during Lubuk Bakung test	12.4–12.6 V
Inverter AC output	208–218 V
Automatic timer	Activated according to the programmed schedule
Auger rotation	Operated during feeder activation
Feed discharge	Consistent discharge observed during tested cycles
Pellet blockage	Not observed during the test period
Automatic feeding operation	Feeding cycles completed during testing
Total feeder power requirement	52 W
Integrated prototype	Operated as an interconnected system during the test period

As shown in Table 5, the PV subsystem provided the largest instantaneous electrical-power output among the renewable-energy sources evaluated. The maximum PV output under feeder load was 60.80 W, equivalent to 116.9% of the 52-W feeder requirement. The maximum laboratory VAWT output of 17.304 W corresponded to 33.3% of the feeder requirement, the maximum Tanjung Api-Api output of 17.93 W to 34.5%, and the Lubuk Bakung maximum of 0.689 W to 1.33%. Figure 9 provides a direct comparison of these maxima against the feeder threshold.

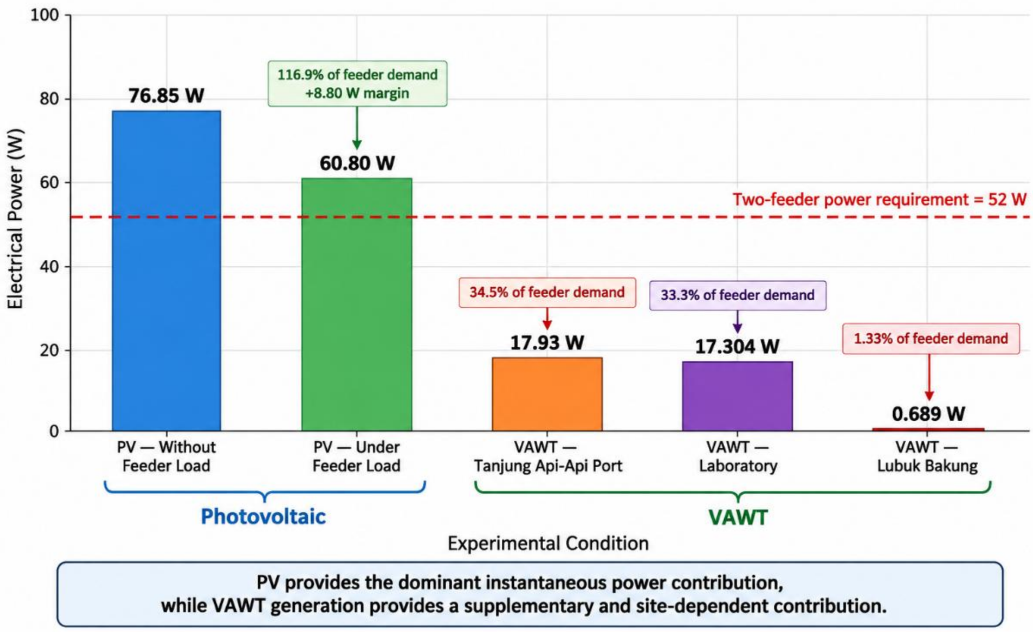

Figure 9. Maximum measured electrical power under different experimental conditions relative to the 52-W automatic feeder requirement.

Because the maxima were recorded under different operating conditions and locations, they were presented individually and were not summed to estimate a simultaneous hybrid-system maximum output.

Battery and Inverter Performance

Battery input voltage during the Lubuk Bakung field test increased only slightly from 12.4 V at 15:00 WIB to 12.6 V at 15:40 WIB. Across the five observations in Table 4, the mean battery input voltage was 12.48 ± 0.084 V, corresponding to a coefficient of variation of approximately 0.67%.

The inverter was separately evaluated under light AC-load conditions. Its measured output remained between 208 and 218 V AC. Relative to the nominal 220-V level, these endpoints corresponded to deviations of approximately −5.45% and −0.91%, respectively. Figure 10 combines the battery-voltage profile and reported inverter-output range.

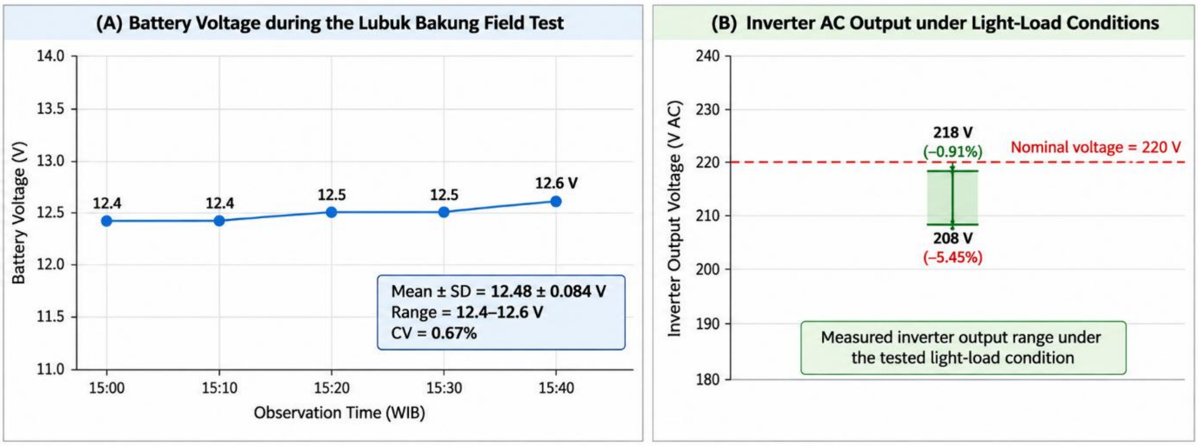

Figure 10. Battery-voltage variation during the Lubuk Bakung field test and measured inverter AC-output range under light-load conditions.

These measurements characterize short-duration voltage behavior during the test conditions; they were not interpreted as battery-autonomy or inverter-efficiency measurements.

Discussion

PV-Dominant Power Architecture and Feeder-Load Adequacy

The results indicate that the developed hybrid system operated primarily as a PV-dominant architecture. Under the maximum reported feeder-load condition, PV generated 60.80 W, exceeding the 52-W instantaneous demand by 8.80 W (16.9%). However, PV output decreased to 46.20 W at 13:00 WIB and 41.75 W at 14:00 WIB. Thus, direct PV generation was sufficient during favorable midday conditions but did not independently satisfy the same instantaneous load throughout the observed daytime period.

This behavior is consistent with hybrid renewable-energy systems in which variable generation is coordinated with storage and load demand (Gajewski & Pieńkowski, 2021; Naderipour et al., 2021; Falope et al., 2024). Battery energy storage is particularly important in PV-based systems because it can buffer short-term mismatches between generation and electrical demand (Rana et al., 2022; Yang et al., 2022; Sayed et al., 2023). In the present architecture, the battery therefore functions as an electrical buffer between intermittent renewable generation and scheduled feeder operation.

The difference between the maximum measured output without feeder load (76.85 W) and under feeder load (60.80 W) should be interpreted as performance under different operating conditions rather than as a conversion-efficiency value. The experiment did not quantify all simultaneous input and output power flows needed to calculate complete system efficiency.

Site-Dependent Contribution of the Vertical Axis Wind Turbine

VAWT electrical-power output differed markedly among the laboratory, Lubuk Bakung, and Tanjung Api-Api conditions. The laboratory mean was 13.395 ± 2.417 W with a maximum of 17.304 W, while Tanjung Api-Api produced 14.00 ± 2.43 W with a maximum of 17.93 W. In contrast, Lubuk Bakung produced 0.612 ± 0.071 W on average and a maximum of 0.689 W. These results demonstrate that the practical electrical contribution of the VAWT varied substantially among the tested environments.

The observed variability is consistent with VAWT research showing that performance depends on wind conditions, rotational behavior, blade geometry, tip-speed ratio, dynamic-stall behavior, and local flow characteristics (Santamaría et al., 2022; Zhang et al., 2021; Awotwe & Alaswad, 2023; Pietrykowski et al., 2023; Keisar et al., 2023, 2024; Lu & Xu, 2024). Blade-level aerodynamic control and turbine operating state can also substantially alter VAWT performance (Le Fouest & Mulleners, 2024), while wake and flow interactions further influence loading and available power (Wei et al., 2021; Huang et al., 2023). These findings support a condition-dependent interpretation rather than a simple assumption that all electrical variables increase monotonically with wind speed.

At Lubuk Bakung, the maximum VAWT output of 0.689 W represented only 1.33% of the instantaneous 52-W feeder requirement. Under these field conditions, the VAWT therefore functioned primarily as a supplementary charging source rather than an independent source capable of directly operating the feeder. By comparison, the Tanjung Api-Api maximum of 17.93 W represented 34.5% of the feeder requirement and was comparable to the 17.304-W laboratory maximum. This contrast reinforces the need for site-specific wind-resource assessment when applying a VAWT to small off-grid loads (Kouloumpis et al., 2020; Trentin et al., 2022; Silva-Llanca & Inostroza-Lagos, 2021; Franchina et al., 2022).

Role of Battery Storage and Power Conditioning

Battery and inverter behavior provide additional support for the buffering role of the storage subsystem. During the Lubuk Bakung test, battery input voltage remained within 12.4–12.6 V, with a mean of 12.48 ± 0.084 V and a coefficient of variation of approximately 0.67%. The limited voltage variation during the observation period indicates comparatively stable battery-side voltage while renewable generation varied. Battery storage is widely used in hybrid renewable-energy systems for this buffering function (Rana et al., 2022; Yang et al., 2022; Sayed et al., 2023).

The inverter provided the complementary power-conditioning function by converting battery-side DC energy to AC voltage for the tested loads. The measured output range of 208–218 V was close to the nominal 220-V level under the tested light-load condition. However, voltage adequacy should not be interpreted as inverter conversion efficiency because DC input power and AC output power were not measured systematically.

Future development could incorporate higher-resolution electrical monitoring, battery state-of-charge estimation, and adaptive source/load control. Monitoring and intelligent control approaches are increasingly applied to renewable-energy systems and aquaculture automation (Boucif et al., 2025; Ubina et al., 2023; Abdullah et al., 2024).

Operational Feasibility for Automatic Fish Feeding

At the system level, the key result was the functional integration of renewable-energy generation with the automatic feeding mechanism. During the observed feeding cycles, the programmable timer activated the DC motor, the motor drove the auger, and pellets were discharged through the outlet. No pellet blockage or mechanical interruption was observed during the test period. These results demonstrate that the generation, storage, power-conditioning, control, and feed-dispensing subsystems could operate as an integrated prototype.

Automatic feeding systems can reduce dependence on manual schedules and improve consistency of feed delivery (El Shal et al., 2021; Chiu et al., 2022; Rahayu et al., 2026). The present study addresses a complementary engineering challenge: providing an off-grid electrical architecture for that automation. In this configuration, feeder operation depended on the combined architecture rather than on instantaneous output from either renewable source alone.

The observed consistency of feed discharge should nevertheless not be interpreted as quantitative feeding precision. The study did not determine dispensed feed mass over replicated cycles, dosing error, or the coefficient of variation of feed delivery. The present evidence therefore supports functional feed dispensing and absence of observed blockage, while quantitative feeding accuracy remains a subject for future testing.

Technical Limitations and Engineering Implications

Several technical observations define the scope of the current prototype. First, the VAWT exhibited slow or unstable startup behavior under very low wind conditions, and the wind-control stage could not consistently initiate charging when turbine output was insufficient. Low-wind startup and operating sensitivity are recognized issues in small VAWT applications (Awotwe & Alaswad, 2023; Keisar et al., 2023, 2024; Le Fouest & Mulleners, 2024).

Second, vibration was observed in the generator support structure under higher rotational conditions. Cable arrangement and electrical connections were also identified as potential sources of avoidable electrical loss, while low current under some field conditions approached the sensitivity limits of the available ammeter. Future iterations should therefore consider stronger support structures, improved electrical connections, and higher-resolution instrumentation. Experimental and numerical VAWT studies similarly emphasize the importance of mechanical configuration and operating conditions (Zhang et al., 2021; Pietrykowski et al., 2023; Lu & Xu, 2024).

Third, field measurements represent relatively short observation periods. They characterize prototype behavior under the tested conditions rather than annual energy yield, seasonal variability, long-term reliability, or component durability. Fourth, complete battery charge–discharge cycles, battery state of charge, usable depth of discharge, inverter conversion efficiency, and total hybrid-system efficiency were not quantified. Accordingly, the evidence supports short-duration battery-voltage stability and inverter-voltage adequacy but not quantitative claims regarding battery autonomy, full charging time, or overall system efficiency.

Contribution to Sustainable Aquaculture Applications

The principal contribution of this study is the integration of functions that are often investigated separately. Previous work has examined automatic fish-feeding technology (El Shal et al., 2021; Chiu et al., 2022; Rahayu et al., 2026), hybrid renewable-energy management (Gajewski & Pieńkowski, 2021; Falope et al., 2024), small-scale VAWT performance (Kouloumpis et al., 2020; Santamaría et al., 2022; Awotwe & Alaswad, 2023), and renewable-energy applications for aquaculture equipment such as pond aeration (Khojim et al., 2023). The present system integrates PV generation, VAWT generation, storage, power conditioning, programmable control, and mechanical feed dispensing within a single prototype.

The findings clarify the functional hierarchy of the architecture: PV provided the dominant instantaneous power contribution, the VAWT supplied a supplementary and site-dependent contribution, the battery buffered short-term mismatch between generation and demand, and the inverter/control components enabled scheduled feeder operation. For small-scale aquaculture facilities with limited access to conventional electricity, this architecture provides a technically feasible pathway toward greater energy independence under the tested conditions. Sustainability claims should nevertheless remain restricted to renewable-energy utilization and reduced grid dependence because life-cycle environmental impacts and economic performance were not quantified.

CONCLUSIONS

This study developed and experimentally evaluated a hybrid renewable-energy automatic fish feeding system integrating PV generation, a VAWT, battery storage, power conditioning, programmable control, and an auger-based feeding mechanism. The prototype operated as an integrated architecture in which PV provided the dominant electrical contribution, the VAWT supplied supplementary generation, and the battery buffered short-term variation between renewable-energy availability and feeder demand.

The PV subsystem produced a maximum output of 76.85 W without feeder load and 60.80 W under feeder-load conditions. At the maximum loaded output, PV exceeded the 52-W requirement of the two feeder units by 8.80 W (16.9%). PV output later decreased to 46.20 W at 13:00 WIB and 41.75 W at 14:00 WIB, demonstrating that direct PV generation alone did not satisfy the feeder requirement throughout the observed daytime period.

VAWT performance varied substantially among the experimental conditions. Laboratory testing produced a mean of 13.395 ± 2.417 W and a maximum of 17.304 W. Tanjung Api-Api produced 14.00 ± 2.43 W on average and a maximum of 17.93 W, whereas Lubuk Bakung produced 0.612 ± 0.071 W on average and a maximum of 0.689 W. The Lubuk Bakung maximum represented only 1.33% of the 52-W feeder requirement, confirming that under those conditions the VAWT functioned primarily as a supplementary source.

Battery input voltage during the Lubuk Bakung test remained within 12.4–12.6 V, while the inverter provided 208–218 V AC under the tested light-load condition.

The automatic feeding mechanism completed the observed programmed cycles without mechanical interruption or pellet blockage. Overall, the findings demonstrate the short-duration technical feasibility of a PV-dominant, VAWT-supplemented, battery-buffered automatic feeding architecture for small-scale aquaculture under the tested conditions.

RECOMMENDATIONS

Future studies should extend field monitoring across different times of day, weather conditions, seasons, and wind-resource environments. The large difference between Lubuk Bakung and Tanjung Api-Api demonstrates that VAWT contribution should be assessed using site-specific wind-resource data before deployment.

A complete electrical energy balance should be established using continuous measurements of PV and VAWT generation, battery state of charge, charge/discharge current, DC input and AC output power, and feeder consumption. These measurements would allow battery autonomy, conversion losses, charging performance, and overall source-to-load efficiency to be quantified directly.

The feeding subsystem should be evaluated gravimetrically by measuring feed mass per cycle, dosing error, repeatability, coefficient of variation, blockage frequency, and performance with different pellet sizes and operating durations. These measurements are required before drawing conclusions about feeding precision or feed-use efficiency.

Engineering improvements should focus on low-wind VAWT startup, reinforcement of the turbine support structure, improved cable routing and electrical connections, and higher-resolution instrumentation. Battery state-of-charge monitoring, low-voltage protection, adaptive source-priority control, and more flexible feeder scheduling should also be considered.

Finally, long-term techno-economic and environmental assessments are recommended. Capital cost, maintenance, battery replacement, energy savings, payback period, and life-cycle environmental impacts should be evaluated to determine whether the demonstrated technical feasibility translates into sustained operational, economic, and environmental benefits.

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The authors declare no conflict of interest.

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Not applicable.

Data Availability
Data availability is not applicable to this article because no new data were created or analyzed in this study.

Author Contributions Statement

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
M. Habib Aulia	✓	✓	✓		✓	✓		✓	✓	✓	✓			
Tresna Dewi	✓	✓		✓	✓					✓		✓		
Yohandri Bow	✓	✓		✓			✓			✓		✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

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