

An Integrated IoT and Solar Energy System for Efficient Water Quality Monitoring at Sustainable Intensive Shrimp Aquacultures

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ABSTRACT

The intensive shrimp farming industry in Indonesia currently faces a significant sustainability challenge due to its heavy reliance on diesel-powered aerators. This dependency is exacerbated by unpredictable fuel prices and a lack of automated water quality management, leaving farms vulnerable to critical environmental fluctuations. In response, this study presents a pilot-scale validation of the "Shrimp Aqua Voltaic" (SAV), a hybrid system that seamlessly integrates solar energy with real-time IoT monitoring and smart aeration control. The primary goal was to assess the system's capacity to restore oxygen levels during critical drops and to conduct a rigorous energy audit within an off-grid framework. This study proposes a solar-powered IoT-based aeration system for real-time monitoring and control of water quality, focusing on Dissolved Oxygen (DO) management in intensive shrimp farming. Field trials were conducted over 5 consecutive days in a controlled test pond, supplemented by a one-day benchmark comparison against standard 3-phase industrial aerators. The results were highly encouraging: the SAV system autonomously detected a simulated hypoxic event (0.8 mg/L DO) and effectively raised oxygen levels to a safe zone (6.8 mg/L) within just one hour—a performance on par with a 1 HP industrial aerator. However,

the energy audit revealed a critical insight for future optimization: the parasitic load from the continuous IoT monitoring system consumes approximately 62% of the daily energy budget. While the SAV system demonstrates mechanical reliability in preventing stock loss, these findings underscore that achieving commercial scalability necessitates electrical optimization, primarily through the implementation of DC coupling for instrumentation alongside the integration of smart power-management algorithms.

Keywords-paddle wheel aerator; solar photovoltaic; IoT; energy efficiency; dissolved oxygen; aquaculture

I. INTRODUCTION

Aquaculture produces the internationally valued *Litopenaeus Vannamei* shrimp, which is essential to the global food supply [1]. In Indonesia, intensive farming methods with elevated stocking densities have gained popularity to improve production and land utilization in response to increasing shrimp exports [2]. This escalation has increased the demand for Dissolved Oxygen (DO) and biological oxygen, resulting in complications [3]. Aeration systems are essential for the survival and growth of shrimp [4]. Economic losses from mass shrimp mortality, primarily due to fluctuations in water quality, impede Indonesia's aquaculture industry. During the night or after substantial precipitation, dissolved oxygen concentrations decrease significantly, exacerbating the issue [5]. Oxygen deprivation events can decimate 40% of shrimp farm populations without immediate intervention [6], resulting in huge annual economic losses [7]. The inadequacy of Indonesia's monitoring systems exacerbates this risk, undermining the economic stability of the shrimp-farming sector and jeopardizing livelihoods [8].

The utilization of diesel-powered aerators in large-scale shrimp farming presents challenges [9, 10]. Indonesian shrimp aquaculture uses diesel generators for aeration purposes. These systems are reliable; nevertheless, their reliance on fossil fuels increases operating expenses and generates carbon emissions [11]. Diesel fuel can comprise roughly 60% of agricultural operating expenses [12]. Reliance on diesel compromises the environmental objectives of contemporary aquaculture. Traditional aeration systems are inflexible and unable to adjust to variations in water quality, increasing the likelihood of oxygen deficiency for shrimp without intervention [13].

Sustainable solar-powered aeration systems can resolve these problems, reducing energy costs by 50–60%, despite the substantial initial expenditure [14, 15]. These methods mitigate carbon emissions, promoting sustainable agriculture [16]. The adoption of solar energy in shrimp farming has been sluggish due to substantial initial costs and farmers' limited awareness of its enduring economic and environmental benefits [17]. Solar-powered aerators equipped with IoT monitoring systems enable real-time adjustments to aeration, thereby improving farm management and reducing shrimp mortality from abrupt changes in water quality [18]. Due to the correlation between shrimp mortality and energy use, systems incorporating solar-powered aerators and sophisticated monitoring technology are essential, as they can reduce diesel consumption and enhance agricultural productivity by responding to real-time changes in water quality [19, 20]. Integrating solar energy with IoT monitoring can reduce shrimp aquaculture costs, improve shrimp health, and mitigate environmental impacts [21], improving the profitability and sustainability of Indonesia's shrimp farming sector [22].

Recent studies have explored ways to use technology to improve energy efficiency and water quality in shrimp farming [23]. In [24], the focus was on research into solar aeration systems and how IoT technologies are used in aquaculture. In [25], a resource assessment of Floating Solar Photovoltaic (FSPV) systems, Photovoltaic (PV) panels that float on water bodies, evaluated the potential for solar radiation and the thermal benefits of water cooling. The findings indicated that FSPV offers promising technical advantages over land-based PV systems. However, this study was limited to resource potential assessment and did not address the application of FSPV under operational loads, such as aerators or aquaculture systems, while automatic control mechanisms are essential for real-time adjustments in aquaculture operations. In addition, improving the visibility of the process by monitoring environmental parameters is essential [26].

In [16], a solar-powered IoT (Internet of Things) system for aquaculture aeration monitored pH (a measure of acidity/alkalinity), temperature, and Total Dissolved Solids (TDS, a measure of dissolved substances in water). Although this study contributed to water quality monitoring, it did not include DO [27–29], the amount of oxygen dissolved in water, a critical parameter for aerator operation in shrimp ponds. In addition, motor-impeller compatibility issues were identified, resulting in reduced aeration efficiency. Recent advances have combined solar-powered systems with IoT-based automatic control to dynamically regulate aeration levels. Aerators, such as paddle wheel aerators, circulate water and increase oxygen content, and are now often integrated with solar PV systems [30]. These integrated systems can reduce energy consumption by up to 30% in commercial aquaculture, significantly reducing operational costs and enhancing sustainability [31]. The integration of paddle wheel aerators with solar PV systems has emerged as a promising approach for shrimp farms, reducing costs and improving oxygenation [32]. Solar aeration systems have strong potential, but some barriers remain in shrimp farming. High upfront costs are a big hurdle, especially for small farms. System complexity and required skills also create challenges [33]. Still, recent studies show that these technologies can improve aquaculture sustainability. For example, in [34], solar paddle-wheel aerators in a 1-hectare pond had lower operational costs and carbon emissions.

Between 2023 and 2025, there has been major progress in solar aeration. The study in [35] reviewed advanced solar energy systems with automated water quality control in intensive shrimp farms. Such systems use solar PV, real-time monitoring, and automatic changes based on DO levels. This cuts energy costs by up to 60% [36] while maintaining optimal pond oxygen levels. Additionally, recent innovations in nanobubble generation, producing extremely small gas bubbles that increase oxygen dissolution in water, and micro-aeration techniques have significantly improved oxygen transfer

efficiency while minimizing energy consumption. These advances strongly reinforce the sustainability and future viability of shrimp farming.

II. METHOD

This research phase employs a systematic Research and Development (R&D) approach to ensure the reliability of the system before its implementation in the field. As demonstrated in Figure 1, the research process begins with a comprehensive review of the existing literature and a Focus Group Discussion (FGD) to determine the specifications for the SAV design. The subsequent stage is the development of technical design documents that describe the mechanical structure of the pontoon and an efficient gearbox transmission system. The subsequent phase involves the fabrication of a prototype, the initial validation of the data, and the selection of corrosion-resistant supporting materials. After the integration of the prototype with the solar system and the IoT module, a series of small-scale tests is conducted to refine the features and produce a final device that is ready for performance validation.



Fig. 1. Block diagram.

A. System Architecture and Research Location

The research was conducted at the experimental test pool of Shipbuilding Polytechnic of Surabaya (PPNS) in Latitude: -7.277814 and Longitude: 112.795709. The SAV system was developed as an independent floating unit with a corrosion-resistant frame based on High-Density Polyethylene (HDPE) pontoons. The primary power source is derived from two 200 Wp monocrystalline solar panels (400 Wp total) managed by an MPPT-type Solar Charge Controller (SCC) to charge a 12V 150Ah LiFePO₄ battery bank. This storage capacity has been designed to accommodate solar intermittency, considering the local average Peak Sun Hours (PSH) of 4.5 hours.

B. Control and Instrumentation Systems

The central control unit employs an ESP32 microcontroller integrated with an industrial water quality sensor circuit to monitor six parameters: pH, DO, temperature, salinity, TDS, and turbidity. The data is transmitted wirelessly (Wi-Fi/NB-IoT) to a cloud server, enabling real-time monitoring, and then displayed on a local Nextion HMI interface. The aerator control mechanism is subject to regulation by a relay that is triggered by the DO parameter threshold. Table I summarizes the specification details of the main components used in the development of the SAV system.

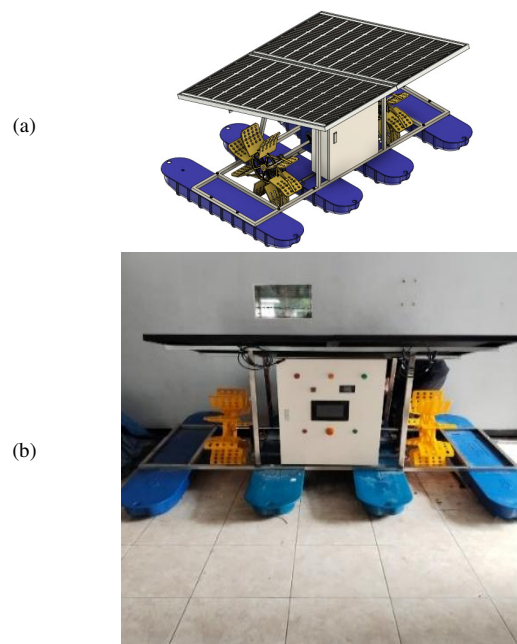


Fig. 2. (a) 3D mechanical design of aerator; (b) finished aerator.

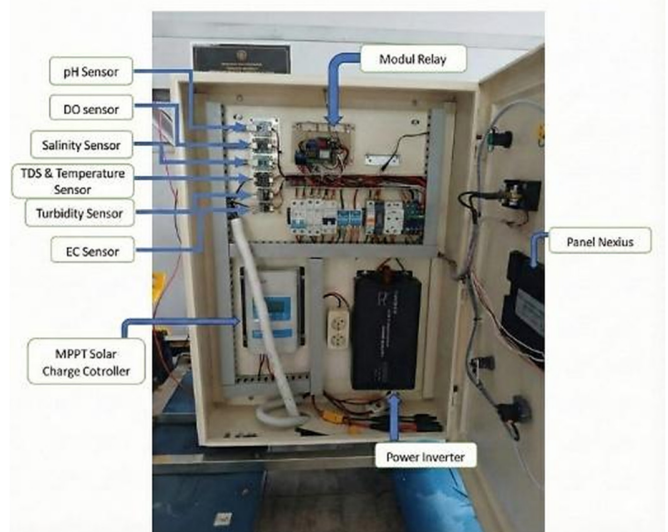


Fig. 3. Solar energy and wireless sensor network.

TABLE I. MAIN SPECIFICATIONS OF COMPONENTS

	Component	Specification	Information
1	Solar Panels	200 Wp × 2 pcs	Used as the primary energy source to drive the aerator system
2	Sensor	pH, DO, Temperature, Salinity, Turbidity, TDS	Monitors water quality conditions in real-time
3	Battery (Control Box)	150Ah, 12V	Stores power for the operation of control systems and sensors
4	Aerator Motor	550W, 220V AC	Moves the wheel to increase DO levels in the water
5	Controller (SCC)	MPPT Type	Sets the battery to optimal charge
6	Microcontroller	ESP32	IoT data processing and communication unit

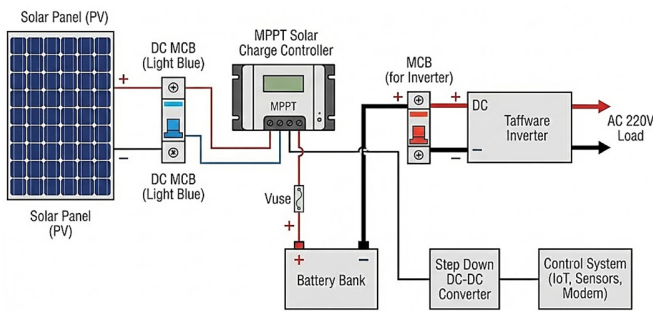


Fig. 4. Solar-powered floating aerator system diagram.

C. Testing Protocol (5-Day Observation)

Field data collection was conducted over five consecutive days (October 20-24, 2025). The testing protocol was designed to cover two main scenarios to validate operational reliability and compare mechanical performance:

1. SAV System Validation Test (5 Days):
 - a. Regular Schedule: Aerator is active during peak sunlight hours (9:00–10:00 a.m.), midday (12:30–1:00 p.m.), and late afternoon (3:00–4:00 p.m.).
 - b. Emergency Response: Automatic activation if DO < 2.0 mg/L (Tested in hypoxia simulation on October 21).
2. Comparative Benchmark Test (1 Day): A special test was conducted for one full day to compare the oxygen transfer rate of the SAV system with that of a conventional aerator. The conditions tested included:
 - a. Negative Control: Without Aerator / Without Impeller.
 - b. Benchmark 1: Windmill with 1 HP 3-Phase Motor.
 - c. Benchmark 2: Windmill with 2 HP 3-Phase Motor.

On October 20, the pond's conditions were artificially altered to simulate a high organic load, which triggered a significant decrease in oxygen levels. This experimental manipulation aimed to assess the system's capacity for recovery. Electrical parameters were recorded concurrently for the purpose of daily energy balance calculations.

$$E_{Balance} = E_{pv} - (E_{Aeration} - E_{parasites})$$

The monitoring display shows an automated scheduling system for the operation of the aerator (Figure 5). It has predefined time slots with a corresponding ON/OFF action that controls the aerator's daily operation. Each schedule is set to repeat every day, enabled or disabled using the toggle switch. Overall, this display helps operators monitor and manage the performance of the aerator efficiently while supporting stable water quality and optimized energy usage.

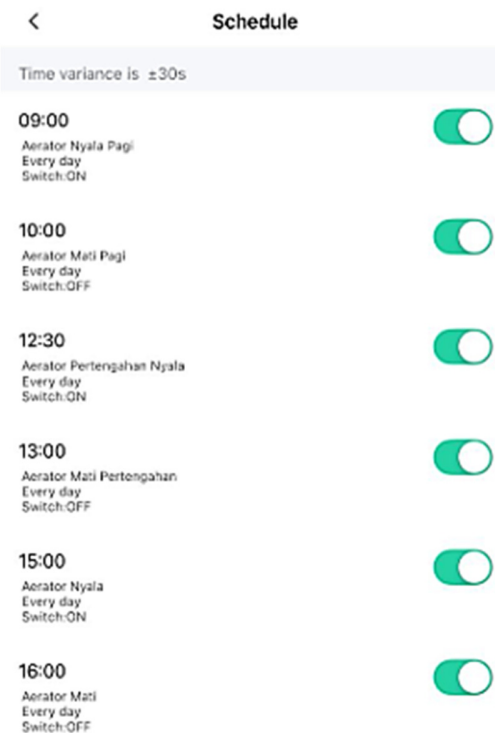


Fig. 5. Aeration schedule scenario.

III. RESULTS AND DISCUSSION

This section presents the results of the implementation and performance analysis of the developed solar-based smart aerator system. The presentation of the results is divided into three subsections. The first is an evaluation of the performance of the user interface (Human-Machine Interface - HMI) in presenting real-time data. The second is an analysis of the dynamics of the water quality parameters in response to aerator operations. The third is an audit of the electrical system's performance to identify energy consumption profiles and opportunities for efficiency improvements. All data presented are the result of field measurements that have been meticulously validated to ensure the system's reliability in supporting sustainable aquaculture productivity.

A. Human-Machine Interface of Water Quality Monitoring System in Vannamei Shrimp Pond

The developed water quality monitoring system successfully integrates an HMI through a website and a Nextion touchscreen. The system displays six parameters in real time, accompanied by a status indicator feature. Parameter values exceeding the critical threshold are marked in red, signifying a status of "Poor," while values within the normal range are marked in green, indicating a status of "Good." Validation was performed using a direct comparison method against industry-standard reference instruments. As summarized in Table I, the system achieved an average accuracy of 98.58%, with an average error of 1.43%. Individual parameter errors remained low (0.65–1.96%), ensuring that the automatic aerator activation is triggered by valid environmental conditions rather than sensor inaccuracies, thus validating the

reliability of the instrument for field use compared with less effective manual methods. Ensuring the accuracy of this data is paramount to guarantee that decisions regarding the activation of automatic aerators are based on valid environmental conditions, rather than sensor reading errors.

TABLE II. SENSOR VALIDATION STANDARD REFERENCE INSTRUMENTS

Parameter	System reading	Reference tool	Error (%)	Accuracy (%)
Water temperature	30.9	30.7	0.65%	99.35%
PH	7.9	7.8	1.29%	98.71%
DO	6.3 mg/L	6.4 mg/L	1.56%	98.44%
TDS	168.0 ppm	165.0 ppm	1.82%	98.18%
Salinity (EC)	0.8 mS/cm	0.79 mS/cm	1.27%	98.73%
Turbidity	1.0 NTU	1.02 NTU	1.96%	98.04%
Average			1.43%	98.57%

Figure 6 shows a prototype web-based dashboard for real-time monitoring via a Nextion HMI. Key parameters, including battery voltage, charging current, and DO, are transmitted to a cloud server with stable updates every 5–10 s, without affecting aeration control performance. For data transmission, the system uses the Wi-Fi/NB-IoT communication protocol to send data to a cloud server. Although the primary focus of this study was on energy and mechanical performance analysis, observations during testing indicated stable data transmission. Communication variables were not measured in depth as they were beyond the scope of the power efficiency analysis. However, operationally, the data delays did not impact the effectiveness of the aeration control system in maintaining pond water quality.

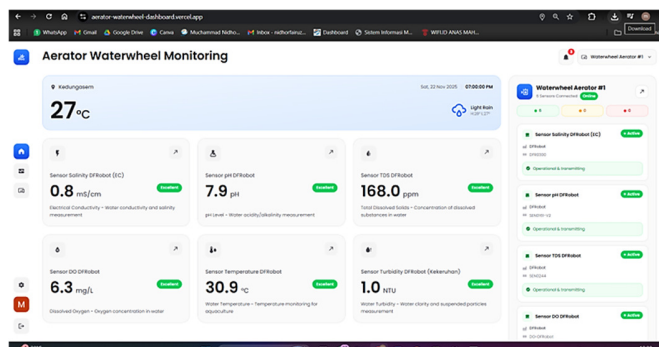


Fig. 6. Solar-powered paddle wheel aerator © interface waterwheel.

B. Oxygen Recovery Performance (DO)

The analysis of time-series data illustrated in Figure 7 offers empirical evidence of the system's responsiveness. The SAV system demonstrated its efficacy in maintaining oxygen levels within the optimal range of 5.5 to 6.5 mg/L during routine testing days (October 20–24) by implementing a scheduled aeration scheme in the test pond with dimensions of 41 m for length, 39 m for width, a water depth of 5 m, and a volume of 7995 m³.

This comprehensive evaluation highlights the design advantages of SAV compared to previous solar aerator studies, such as [16], where, despite the system being integrated with

IoT, the absence of DO sensors and mechanical compatibility issues between the VG45 DC motor and the impeller resulted in a low rotational speed. As a result, air bubble production was minimal, as reflected in the stagnation of pond pH under poor conditions (6.92–7.34) during testing. In contrast, the SAV system in this study used a 550W motor calibrated with the impeller load, resulting in strong agitation that was proven to be able to significantly restore water parameters.

The data indicate a pronounced response on October 21, when the pond experienced a severe hypoxic condition, with DO levels dropping to 0.8 mg/L at 08:00 WIB. Following automatic aerator activation, DO levels recovered rapidly to 6.80 mg/L by 10:00 WIB. Such a rapid increase of 6.0 mg/L within one hour demonstrates that the Oxygen Transfer Rate (OTR) of the 550W paddle-wheel aerator is sufficient to reverse acute hypoxia under pilot-scale pond conditions. Subsequent data showed a return to stable daily patterns, validating the robustness of the DO-based control logic implemented.

The time-series analysis presented in Figure 7 provides a comprehensive overview of the performance of the SAV system during the stress testing phase in the test pond. Before the systematic intervention began on October 20, the average DO level of the pond was recorded at 3.3 mg/L. During the intensive testing period (October 20–24), the graph explicitly shows the system's ability to detect and respond to critical hypoxia simulation conditions (0.8 mg/L) to reach a safe recovery zone (6.8 mg/L) in just one hour. This visualization is supplemented with error bars that represent logical estimates of spatial variation to ensure the representativeness of sensor data throughout the 7,995 m³ test pond volume. After the testing phase ended on October 25, the system consistently showed DO level stability in the range of 5.5 to 8.3 mg/L, which also validated the reliability of the autonomous control algorithm in maintaining environmental quality on an ongoing basis.

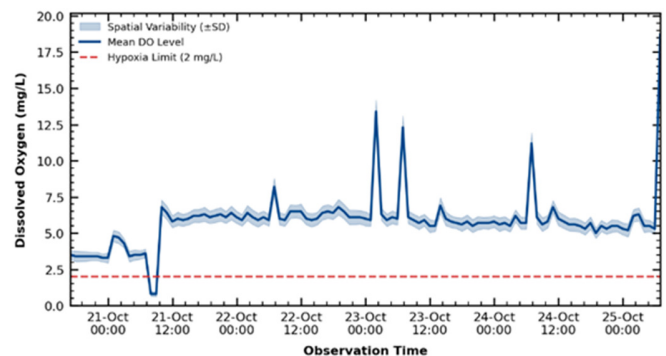


Fig. 7. Graph of DO changes over 5 days.

A comparative analysis with 3-phase aerators was performed to compare the performance of the SAV system in the context of industry standards over a 24-hour cycle, illustrated in Figure 8. The evaluation of the test results indicated that in the absence of mechanical intervention, as evidenced by the negative control condition characterized by the maximum decline in DO levels, the pond exhibited low oxygen levels, falling below the equilibrium of 2.79 mg/L at

5:00 a.m. This study elucidates the extent of the risk of hypoxic conditions for intensive aquaculture without systemic protection and adequate aeration.

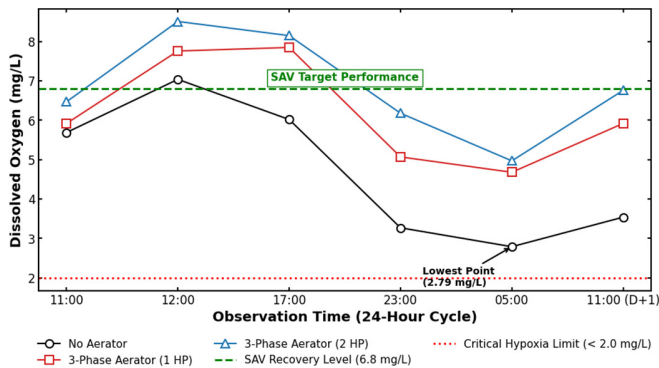


Fig. 8. DO performance benchmark: Conventional 3-phase aerator vs. SAV system.

The industrial aerator units operating at 1 HP and 2 HP demonstrated stable, continuous capability in maintaining oxygen saturation throughout the night. Specifically, the 1 HP unit demonstrated optimal performance, attaining a minimum DO level of 4.68 mg/L, while the 2 HP unit exhibited efficacy from a higher baseline level of 4.97 mg/L. However, SAV, which operates on a power budget of 550W or 0.75 HP as a battery, also exhibited an aggressive response after installation. In critical conditions with a level of 0.8 mg/L, the battery-powered SAV demonstrated a DO track of up to 6.80 mg/L within a span of one hour. This level of oxygenation exceeds the maximum stable level of the average 1 HP aerator and approaches the oxygen content of a 2 HP aerator. Thus, this investigation confirms the efficacy of the sand trap design in facilitating oxygen transfer, even in the presence of competing demands from additional power points and energy autonomy.

The mechanical effectiveness of the SAV aerator is reinforced through quantitative calculations of the OTR based on empirical data obtained during the recovery phase. Considering the dimensions of the test pond (41x39x5 m). Calculations using the mass transfer equation produced an OTR_{actual} value of 47.97 kg O₂/hour.

$$OTR_{actual} = \frac{(C_{akhir} - C_{awal})}{\Delta t} \times V \times 10^{-3} = \frac{(6.8 - 0.8)}{1 \text{ hour}} \times 7,995m^3 \times 10^{-3} = 47.97kg \text{ O}_2/h$$

This calculation is also based on the basic equation of oxygen mass transfer.

$$OTR = K_L a \cdot (C_s \cdot C) \cdot V$$

Although this figure indicates very aggressive local saturation due to the large volume of water, the results prove the aerator's ability to distribute oxygen quickly during emergency conditions. Referring to the literature standard [4], a 0.55 kW water wheel generally has a laboratory oxygen transfer capacity ranging from 0.60 to 1.37 kg O₂/hour. The SAV's achievement in these field conditions is considered highly efficient, given that the testing was conducted at high

temperatures (31.81°C) and high salinity (32.18 ppt), which inherently reduce oxygen saturation solubility (C_s). The integration of this quantitative analysis confirms that the SAV system design has met the mass transfer principles required to support intensive aquaculture ecosystems.

C. Energy Balance Analysis and Parasitic Load Issues

In an off-grid solar-powered system, the total daily energy consumption is the sum of the active aeration load and the continuous auxiliary (parasitic) loads associated with monitoring, control electronics, and power conversion. Therefore, parasitic loads do not reduce the aeration energy demand but instead add to the total energy requirement that must be supplied by the PV-battery system.

1) Solar Radiation Profile and PV Plant Output

The performance of the power generation was evaluated by analyzing the solar irradiation curve over time. As demonstrated in Figure 9, which presents the relationship between solar radiation and power output, the system manifests pronounced intermittent characteristics.

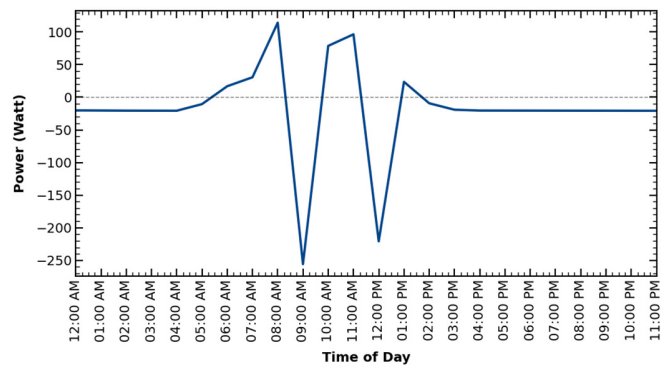


Fig. 9. Power consumption over time.

Based on the analysis of the graph, the following performance data was obtained:

1. Peak Hour: The highest point of energy production was identified at 08:00 WIB.
2. Maximum Power Output: The highest power successfully converted by the system is 114.28 W.
3. Rather than representing PV conversion efficiency, the observed power output is discussed here as a system-level utilization ratio under real operating conditions. Since the installed Wp rating refers to Standard Test Conditions (STC), it does not correspond to the actual solar irradiance received by the panels during field operation, and the system's efficiency at peak conditions is calculated using the following equation:

$$\eta_{PV} = \left(\frac{P_{Actual}}{P_{Rated}} \right) \times 100\% = \left(\frac{114.28 \text{ W}}{200 \text{ Wp}} \right) \times 100\% = 57.14\%$$

This efficiency of 57.14% indicates a substantial performance disparity. The observed inefficiency can be attributed to two primary factors:

- a. Thermal Derating: The elevated surface temperatures of panels in tropical environments inherently diminish the efficiency of silicon cells [14].
- b. SCC regulation plays a pivotal role. As the battery approaches full voltage (float state), the Solar Charge Controller (SCC) limits the current intake to prevent overcharging, thereby ensuring that the potential PV power is not fully absorbed.

2) Dominance of Parasitic Load

An analysis of daily energy consumption distribution reveals an imbalanced profile for small-scale autonomous systems:

- Aeration Energy (Active): ~322 Wh (38% of total).
- Monitoring Energy (Passive/Parasitic): ~528 Wh (62% of total).

The findings indicate that 62% of daily energy is consumed merely to maintain the operational readiness of the monitoring system and inverter for a 24-hour period (Figure 10). The high parasitic load experienced in the system is attributable to its specific topology, which utilizes AC inverters to provide uninterrupted power to small electronic devices, such as sensors and microcontrollers. In off-grid applications, this inefficiency necessitates a substantially larger and more expensive battery capacity. The recommended technical solution is to migrate to a DC-Coupling topology, where IoT devices are supplied directly from the battery via a DC-DC buck converter, thereby eliminating the inverter's standby power loss. This strategy is estimated to reduce base energy consumption by up to 40%.

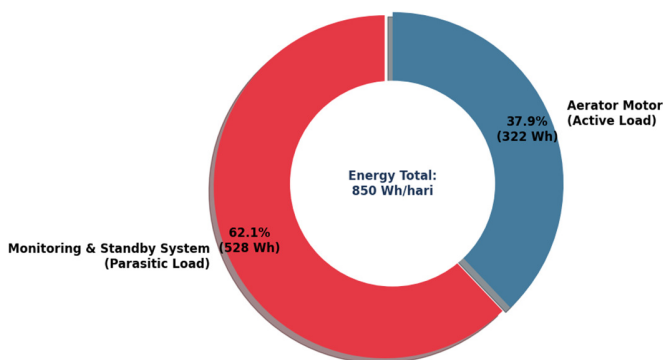


Fig. 10. Distribution of daily energy consumption.

The integration of IoT and automation is increasingly prevalent across numerous scientific disciplines, including agricultural sciences. In contrast, the aquaculture sector has yet to fully realize the advantages of these modern technological advancements. Although initial capital investment remains a significant challenge, high operating costs represent a critical impediment that must be addressed when designing innovative aeration systems [16]. The efficiency of an aerator is a critical determinant in its selection and application, as it directly influences both capital expenditure and long-term operational costs. Consequently, there remains significant potential for

structural refinement and performance optimization of paddle wheel aerator designs [16].

IV. CONCLUSION

This study successfully validated the performance of the Shrimp Aqua Voltaic (SAV) system through a five-day pilot-scale field test. Mechanically, the system demonstrated reliability, successfully restoring dissolved oxygen levels from a lethal level of 0.8 mg/L to an optimal level of 6.8 mg/L within a span of one hour, thus ensuring the preservation of the shrimp stock. Benchmarking results indicated that while the SAV system's oxygen transfer performance is comparable to that of conventional three-phase aerators, its power profile is heavily skewed by the monitoring system. This parasitic load accounts for 62% of total energy usage, surpassing the aeration process itself (38%). Therefore, commercial scalability depends on electrical optimization, specifically through DC coupling for instrumentation and the integration of intelligent power-management algorithms. Future research will focus on long-term testing at commercial scale, as well as the integration of GPS systems and rudder mechanisms to enable autonomous positioning and improved spatial aeration control in the floating SAV system.

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