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Design and performance evaluation of a solar-powered electrical system for shrimp pond aerators

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Abstract

This study presents the design and performance evaluation of a solar-powered electrical system for shrimp pond aerators. The system was developed to provide a reliable off-grid energy solution by considering electrical load requirements, photovoltaic performance, and energy storage configuration. A 300 Wp photovoltaic panel, battery-based energy storage, and a DC motor aerator with a rated power of 250 W were utilized in the proposed system. Experimental testing was conducted under Standard Test Conditions (STC) and normal operating conditions through field measurements at Setu Hambaro, Cileungsi, Bogor. The results show that the photovoltaic system delivered an effective output power of approximately 281 W under normal operating conditions, providing a safety margin of around 12% above the aerator power requirement. The measured system efficiency ranged from 9.84% under STC to 11.58% under normal field conditions, reflecting typical efficiency variations caused by environmental factors and system-level losses. The findings indicate that the proposed electrical system design is capable of maintaining stable aerator operation without abrupt power fluctuations. Despite reduced efficiency compared to nominal photovoltaic module ratings, the system performance remains within acceptable limits for standalone photovoltaic applications. Overall, the results confirm that the proposed solar-powered electrical system is technically feasible and suitable for shrimp pond aerator applications in areas with limited access to grid electricity.

Keywords: photovoltaic performance, renewable energi, shrimp pond aerator, solar-powered system

1. Introduction

Aeration systems are essential components in intensive shrimp aquaculture, as they maintain adequate dissolved oxygen levels that directly influence shrimp growth, feed efficiency, and survival rates [1], [2]. Continuous aerator operation is particularly critical in high-density shrimp ponds, where oxygen depletion can occur rapidly during nighttime or periods of high biological activity [3]. Consequently, the reliability of the electrical power supply for aerators plays a vital role in ensuring stable pond conditions.

In many coastal and rural aquaculture regions, access to reliable grid electricity remains limited or unstable [4], [5]. Shrimp farmers often depend on diesel generators to support aerator operation, which results in high operational costs, fuel dependency, and increased greenhouse gas emissions [6]. These challenges highlight the need for alternative power solutions that are economically feasible, environmentally friendly, and capable of supporting continuous operation in off-grid conditions.

Solar photovoltaic (PV) technology has been widely adopted as a renewable energy solution for off-grid applications due to its modularity, declining installation costs,

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and compatibility with battery-based energy storage systems [7], [8]. Several studies have demonstrated the potential of solar-powered systems in supporting agricultural and aquaculture activities, including water pumping, lighting, and aeration [9]–[11]. However, the successful implementation of a solar-powered aerator system depends strongly on proper electrical design, particularly in terms of load estimation, photovoltaic sizing, battery capacity, and power regulation.

The electrical performance of off-grid solar systems is influenced by various factors such as solar irradiance variability, ambient temperature, battery characteristics, and motor load behavior [12], [13]. Inadequate system sizing can lead to unstable voltage levels, reduced battery lifespan, and insufficient power supply during extended operating periods [14]. Therefore, performance evaluation of the electrical subsystem including power generation efficiency, energy storage stability, and motor drive characteristics is necessary to ensure reliable and long-term operation.

In addition to power generation and distribution, basic monitoring and control systems can enhance the operational reliability of solar-powered electrical systems. Microcontroller-based platforms enable real-time monitoring of electrical parameters and environmental conditions, allowing users to remotely supervise system performance and identify potential faults at an early stage [15], [16]. While such systems do not replace the core electrical design, they function as supporting tools that improve system manageability, particularly in remote aquaculture locations.

Despite numerous studies on solar energy utilization in aquaculture, comprehensive evaluations of solar-powered electrical systems specifically designed for shrimp pond aerators remain limited. Many existing works focus on photovoltaic performance or mechanical aerator design independently, without assessing the integrated electrical system as a whole. This study addresses this gap by presenting the design and performance evaluation of a solar-powered electrical system for shrimp pond aerators. The proposed system integrates a photovoltaic power source, battery-based energy storage, and a DC motor-driven aerator, with a microcontroller-based monitoring system included as a supporting feature. The objectives of this research are to design an off-grid electrical system suitable for shrimp pond aeration and to evaluate its performance under standard and field operating conditions.

2. Research Method

2.1 System Overview

This study employed an experimental research method to design and evaluate a solar-powered electrical system intended for shrimp pond aerators operating in off-grid environments. The proposed system consists of a photovoltaic (PV) power source, a battery-based energy storage unit, a DC motor-driven aerator, and a supporting monitoring subsystem. The electrical configuration was designed to ensure continuous aerator operation while maintaining system reliability under varying environmental conditions.

Figure 1 illustrates the overall block diagram of the proposed electrical system. Electrical energy generated by the photovoltaic panel is regulated through a charge controller and stored in a battery system. The stored energy is then supplied to the DC motor via a motor driver to operate the aerator. A microcontroller-based monitoring unit is incorporated as a supporting component to observe system conditions without affecting the core electrical performance. The primary focus of this research is placed on the electrical performance of the system, while the monitoring subsystem functions solely as a supporting feature.

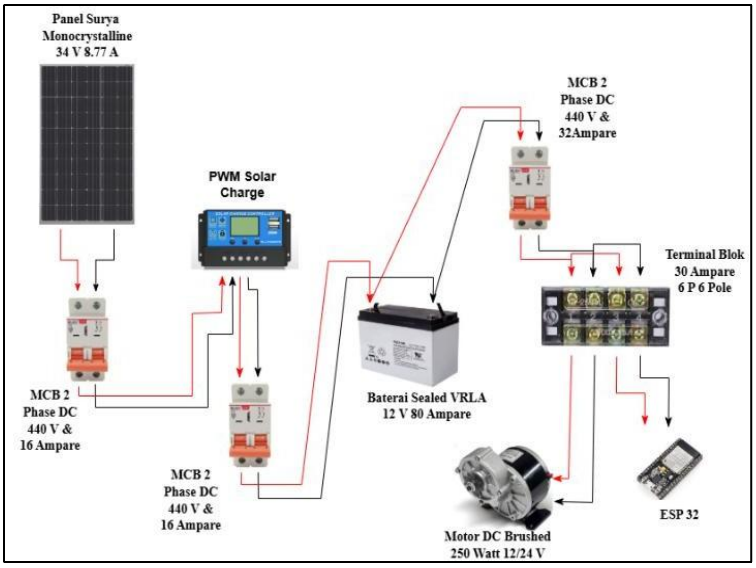

Figure 1. Wiring diagram of the proposed solar-powered electrical system

2.2 Electrical Load Analysis

The electrical load analysis was conducted to determine the energy requirements of the shrimp pond aerator. The load calculation was based on the rated power of the DC motor and its daily operating duration. The total daily electrical energy consumption was calculated using Equation (1).

$$E_d = P_m \times t \tag{1}$$

where E_d represents the daily energy demand (Wh), P_m denotes the rated motor power (W), and t is the operating time (hours). This calculation served as the basis for sizing the photovoltaic panel and battery capacity to ensure sufficient energy availability for continuous aerator operation [17], [18].

2.3 Solar Photovoltaic and Battery System Design

The photovoltaic system was designed using a monocrystalline solar panel with a rated capacity of 300 Wp. Energy storage was provided by a 24 V, 80 Ah valve-regulated lead-acid (VRLA) battery to support off-grid operation during periods of low solar irradiance and nighttime operation. A pulse-width modulation (PWM) charge controller was employed to regulate the charging and discharging processes and protect the battery from overcharging and deep discharge. The main power flow path consists of the photovoltaic panel, PWM charge controller, VRLA battery, and electrical load. Electrical energy generated by the photovoltaic panel is regulated by the charge controller and stored in the battery before being supplied to the load, supporting stable voltage regulation and energy distribution throughout the system.

2.4 Motor Drive and Control System

A brushed DC motor rated at 24 V and 250 W was used to drive the shrimp pond aerator. The motor was controlled using a BTS7960 motor driver, which provides adequate current handling capability and bidirectional control suitable for the application. This motor drive configuration allows stable operation under varying load conditions while maintaining electrical efficiency and system reliability.

2.5 Monitoring and Supporting Control System

A microcontroller-based monitoring system was implemented using an ESP32 platform to support system supervision. Temperature data were collected using DS18B20 sensors, and operational information was transmitted wirelessly for remote observation. This monitoring subsystem was designed to provide real-time system status information without influencing the electrical load characteristics or power distribution of the primary system.

2.6 System Development Flowchart

System The overall research procedure followed a structured development sequence, as illustrated in Figure 2. The process began with a literature review and electrical load requirement analysis, followed by system design, component selection, and assembly of the electrical system. System integration and testing were then conducted to evaluate performance and verify operational feasibility. The flowchart highlights the sequential steps involved in system development and testing, ensuring a systematic and replicable research process.

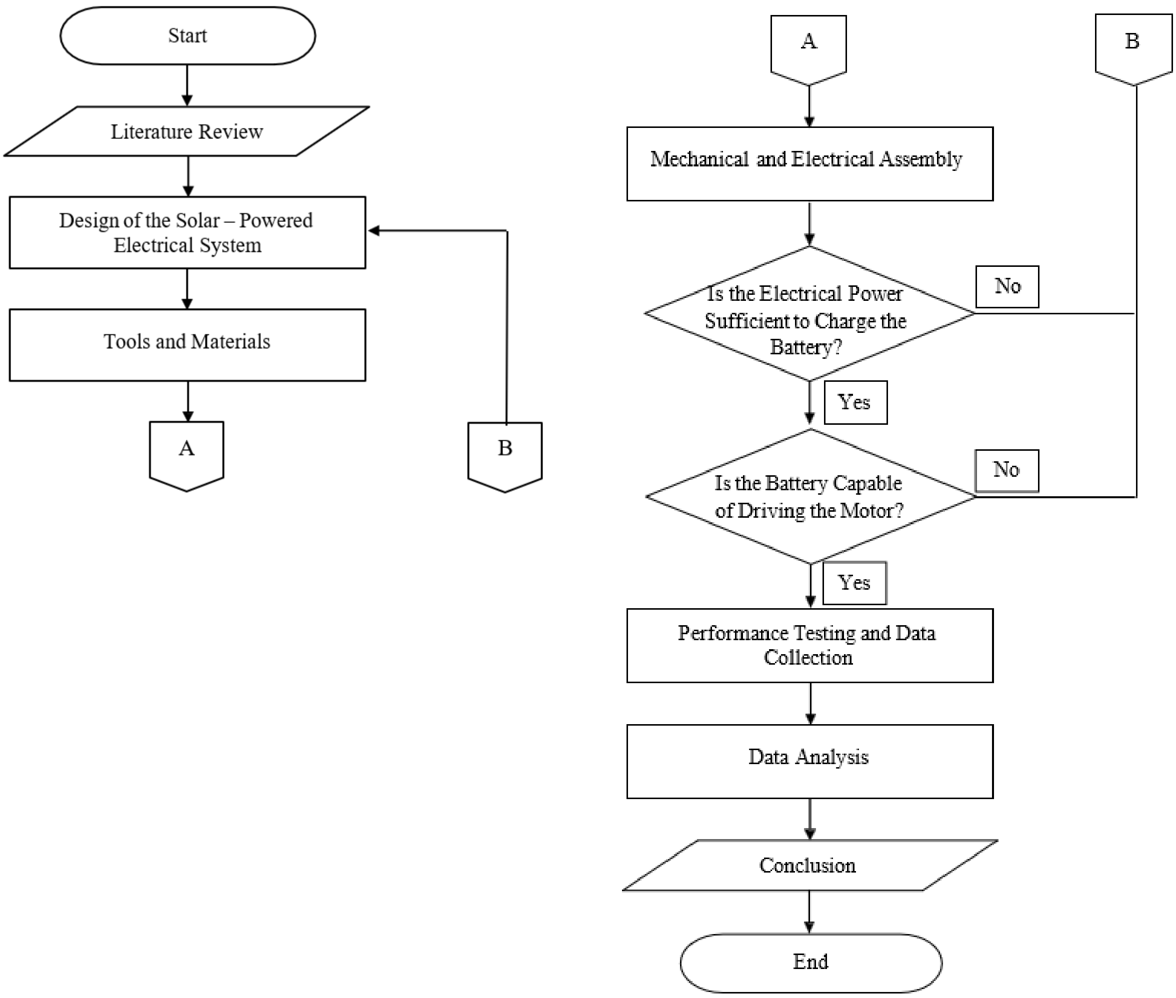

Figure 2. Methodological flowchart of system design and experimental evaluation

2.7 Performance Testing Procedure

System performance was evaluated through experimental testing under field operating conditions. The testing procedures included photovoltaic output measurements, battery voltage stability assessment, and overall system operation analysis during aerator operation. Electrical parameters such as voltage, current, and power were measured using standard electrical measurement instruments. The collected data were analyzed to evaluate system efficiency, energy stability, and operational feasibility of the proposed solar-powered electrical system for shrimp pond aerators.

3. Result and Discussion

This section discusses the electrical performance of the proposed solar-powered electrical system for shrimp pond aerators based on experimental data and design specifications. The discussion focuses on photovoltaic module characteristics, system planning suitability, and effective power output under real operating conditions. All analyses are derived strictly from the tables and figures presented in this study.

3.1 Solar Panel Efficiency and Design Suitability

The specifications of the photovoltaic panel used in this study are presented in Table 1. The panel has a nominal capacity of 300 Wp, with an open-circuit voltage (Voc), maximum power voltage (Vmp), and current ratings suitable for standalone photovoltaic applications.

The selection of this panel capacity was based on the electrical load requirement of the shrimp pond aerator, which utilizes a 250 W DC motor. According to photovoltaic system design guidelines, the installed PV capacity should exceed the nominal load to compensate for efficiency losses due to temperature, irradiance variability, and power conversion losses. The 300 Wp panel therefore provides a design margin of approximately 20%, which aligns with recommended practices for off-grid solar-powered systems [19]–[21].

Table 1. Specifications of the photovoltaic panel used in the system

Type Panel	ST SOLAR
Max Power (*Pmax*)	300 Wp
Max Power Voltage (Vmp)	34.2 V
Max Power Current (Imp)	8.77 A
Open Circuit Voltage (Voc)	41.04 V
Current at Max Power (Isc)	9.3 A
Weight	14.3 Kgs
Size	(1310 × 1134 × 35) mm

The technical specifications listed in Table 1 indicate that the selected photovoltaic panel is suitable for standalone off-grid applications. The voltage and current ratings are compatible with the battery charging system and the electrical load requirements of the aerator motor.

3.2 Comparison of PLTS Design Planning for Aerator Applications

A comparison of photovoltaic system planning for aerator applications is summarized in Table 2, which presents the relationship between planned photovoltaic capacity, electrical load demand, and system feasibility. The data in Table 2 show that the selected photovoltaic configuration meets the minimum power requirement for aerator operation while maintaining sufficient reserve capacity. Compared to designs that utilize photovoltaic capacities equal to or lower than the motor rating, the proposed system demonstrates improved operational reliability, particularly under fluctuating environmental conditions. This comparison confirms that the photovoltaic system planning adopted in this study is technically feasible and appropriate for shrimp pond aerator applications, where continuous operation is essential to maintain dissolved oxygen levels.

Table 2. Comparison of photovoltaic system planning for shrimp pond aerator applications

Panel Configuration	Total Power (Wp)	Daily Energy (Wh)	Evaluation
2 × 200 Wp	400	2000	Sufficient, limited safety margin
2 × 250 Wp	500	2500	Sufficient, weather-dependent
2 × 300 Wp	600	3000	Most stable and reliable

Table 2 presents a comparative design analysis of alternative photovoltaic configurations based on literature and design estimation, while the experimental system implemented in this study utilizes a single 300 Wp photovoltaic panel.

3.3 Effective Power Output Solar Panel Under Field Testing

The effective electrical output of the photovoltaic panel was evaluated through field testing conducted at Setu Hambaro, Cileungsi, Bogor. The measured output power data are presented in Table 3, while the efficiency trend is illustrated in Figure 4.

Based on Table 3, the photovoltaic panel produced an effective output power of approximately 281 W under normal operating conditions. When compared to the rated capacity of 300 Wp, this represents a power reduction of approximately 6–7%. Such reductions are common in real-world photovoltaic systems due to increased operating temperatures and non-uniform irradiance.

According to photovoltaic performance studies, output power reductions between 5% and 20% under field conditions are considered acceptable for standalone systems. Therefore, the measured output power in this study falls well within the expected operational range.

Table 3. Photovoltaic output power measured during field testing at Setu Hambaro, Cileungsi, Bogor

Time	Voltage (V)	Current (A)	Power (W)
12.00	28.3	9.93	281.02
12.10	28.2	9.88	278.62
12.20	28.3	8.83	249.89
12.30	28.1	9.68	272.01
12.40	28.4	10.3	292.52
12.50	28.2	9.72	274.10
13.00	28.0	9.78	273.84
13.10	28.3	9.30	263.19
13.20	28.3	8.91	252.15
13.30	28.0	8.75	245.00
13.40	27.5	7.95	218.63
13.50	28.3	8.03	227.25
14.00	27.8	6.68	185.70

Table 3 shows that the photovoltaic system produced a maximum effective output power of 292.52 W during peak irradiance conditions. The average output power of approximately 281 W indicates a reduction of around 6–7% compared to the rated panel capacity, which remains within acceptable limits for real-world photovoltaic systems.

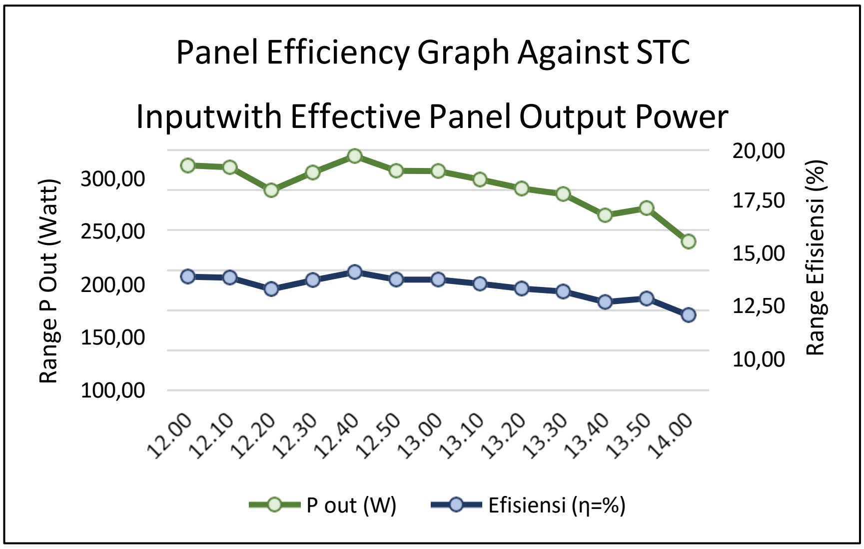

Figure 3. Solar panel efficiency curve under Standard Test Conditions (STC) and normal operating conditions

Figure 3 illustrates that the efficiency under normal operating conditions is consistently lower than under STC due to increased ambient temperature and irradiance fluctuation. However, the efficiency trend remains stable without abrupt degradation, indicating reliable photovoltaic performance during system operation.

3.4 Efficiency Characteristics under STC and Normal Operating Conditions

Figure 3 illustrates the efficiency characteristics of the photovoltaic panel under STC and normal operating conditions. Under STC, the panel exhibits higher efficiency due to controlled irradiance and temperature conditions. In contrast, under normal operating conditions, efficiency decreases due to ambient temperature rise and irradiance fluctuations.

Despite this reduction, the operational efficiency remains sufficient to supply electrical power to the aerator system. The efficiency curve under normal conditions shows a stable trend without abrupt drops, indicating consistent electrical performance and absence of excessive electrical or thermal stress. The stability observed in Figure 3 is particularly important for aquaculture applications, where uninterrupted aerator operation is required to maintain water quality and shrimp health.

Table 4. Comparison of photovoltaic efficiency under STC and normal operating conditions

Condition	Input Power (W)	Output Power (W)	Efficiency (%)
STC (100 W/m^2, 25° C)	2967.80	292.15	9.84
Normal Field (890 W/m^2, 33° C)	2524.36	292.52	11.58

The calculated efficiency under field conditions shown in Table 4 reflects effective power utilization based on real-time irradiance and operating conditions, rather than intrinsic module efficiency, and therefore should not be directly compared with STC-rated efficiency.

3.5 Discussion

The combined results from Tables 1–3 and Figure 4 confirm that the proposed solar-powered electrical system is capable of supporting shrimp pond aerator operation. The effective output power of approximately 281 W exceeds the motor power requirement of 250

W, providing a safety margin of about 12%.

This margin compensates for power losses in the motor driver, wiring, and battery charging processes. The inclusion of a 24 V battery system further enhances reliability by stabilizing voltage and ensuring continuous operation during periods of reduced solar irradiance.

Overall, the quantitative analysis demonstrates that the system design adequately accounts for real-world efficiency losses and provides reliable electrical performance for off-grid shrimp pond aerator applications. The monitoring subsystem functions solely as a supporting feature and does not affect the electrical performance outcomes discussed in this section [22]–[25].

4. Conclusion

This study has presented the design and performance evaluation of a solar-powered electrical system for shrimp pond aerators. The system was designed based on electrical load requirements and photovoltaic performance considerations to ensure reliable off-grid operation. The experimental results show that the photovoltaic system is capable of delivering an effective output power of approximately 281 W under normal operating conditions, which exceeds the aerator motor power requirement of 250 W. This provides a practical safety margin of around 12%, allowing the system to compensate for electrical losses and environmental variations. The measured photovoltaic efficiency ranged from 9.84% under STC to 11.58% under normal field conditions, which remains within acceptable limits for real-world standalone photovoltaic systems when system-level losses are considered. Field testing conducted at Setu Hambaro, Cileungsi, Bogor, confirmed stable electrical performance without abrupt power fluctuations. The results demonstrate that the selected photovoltaic capacity, battery configuration, and electrical components are appropriate for continuous shrimp pond aerator operation.

Overall, the proposed solar-powered electrical system is technically feasible and suitable for application in shrimp farming environments, particularly in locations with limited access to grid electricity. Future work may focus on long-term performance evaluation and optimization of energy management strategies to further improve system efficiency and operational reliability. Although the obtained safety margin is sufficient for short-term and controlled operation, long-term deployment may require additional photovoltaic capacity to account for component aging and seasonal irradiance variation.

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Declarations

Author Contributions. J.W.: conceptualization, solar power system design, research methodology design, experimental implementation, data collection, data analysis, and initial manuscript drafting. R.N.J.: electrical system design and evaluation, system component selection, supervision of experimental implementation, and manuscript review and editing. I.:

system assembly and integration, collection and processing of experimental test data, field testing, and validation of experimental results. H.R.: research supervision, evaluation of research results, validation of the methodology and experimental results, manuscript review and editing, and final approval of the manuscript.

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Conflict of Interest. The authors declare no conflict of interest.

Data Availability. The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Ethical Approval. Not applicable, as this study did not involve human participants or animals.

Use of Artificial Intelligence (AI). The authors declare that the use of artificial intelligence (AI)-based tools, if any, during the preparation of this manuscript was limited to language editing. AI-based tools were not used to generate, manipulate, or determine the scientific content, experimental data, analysis, or conclusions of the research. The authors remain fully responsible for the entire content of the manuscript.

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