

Article

Techno-Economic and Environmental Feasibility of a Solar PV-Based Power Supply System for Paddle Wheel Aerator Operation in Aquaculture Farms

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Abstract

According to the United Nations Food and Agriculture Organization, global aquaculture production reached a record high in 2022, surpassing capture fisheries for the first time. In Brunei Darussalam, the fisheries sector has exhibited steady growth over the past two decades. From an energy consumption perspective, the aquaculture industry is among the electricity-intensive sectors, with demand varying according to the size, layout, and number of ponds in operation. Aeration of aquaculture ponds, particularly intensive ponds, is a critical requirement, and while it is essential to achieve expected production levels, it also represents a major component of operational cost. Aerators are the most power-consuming equipment in aquaculture farms, and paddle wheel aerators generally operate continuously (24 h/day). The monthly energy consumption of a two-impeller paddle wheel aerator is 537.120 kWh. This paper discusses the techno-economic and environmental feasibility of a solar PV-powered energy supply system for paddle wheel aerator operation in aquaculture farms. A case study conducted at an operational aquaculture farm equipped with a hybrid PV system for aeration is analysed in detail. Furthermore, the economic performance of the PV system is evaluated at different penetration levels (10%, 25%, and 50%). The results indicate that solar PV integration provides substantial electricity cost savings, with increasing benefits at higher penetration levels. The payback period (PB) is 8.3 years for a 12.16 kWp (10%) system and 6.9 years for a 60.81 kWp (50%) system, with corresponding returns on investment (ROI) of 2.80% and 3.65%, respectively. The levelised cost of electricity is BND 0.036/kWh at 25% penetration (30.4 kWp) and BND 0.034/kWh at 50% penetration, representing 71.4% and 73.01% reductions, respectively, compared to grid electricity tariffs. At 50% PV penetration, monthly CO₂ emissions are reduced by 6242.71 kg, with a lifetime reduction of 1872.813 tonnes.

Keywords: aquaculture; aerator; energy demand; solar photovoltaic; sustainability; emission reduction; SDG 7; SDG12; SDG13



Academic Editor: Yagang Zhang

Received: 19 November 2025

Revised: 21 January 2026

Accepted: 23 January 2026

Published: 2 March 2026

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1. Introduction

The aquaculture industry has experienced notable growth over the past few decades. According to the Food and Agriculture Organization (FAO), the global aquatic animal production in 2022 reached 94.4 million tonnes, accounting for approximately 51% of the total aquatic animal production [1]. The fisheries sector in Brunei has experienced steady expansion in recent years, particularly in prawn aquaculture. Brunei's prawn aquaculture sector is export-oriented, with the largest producers exporting over 80% of their total production, highlighting the economic significance of the sector [2].

The growth, survival, and productivity of aquatic animals are strongly influenced by the dissolved oxygen (DO) concentration in water. For warm-water aquaculture species, a DO level in the range of 4–7 mg/L is generally required to sustain healthy growth, while concentrations between 7 and 9 mg/L are considered optimal for most stream fish species [3]. Photosynthesis by aquatic plants and algae, together with the diffusion of atmospheric oxygen across the water surface, are natural processes that enhance dissolved oxygen content in aquatic ecosystems [4]. Figure 1 represents the natural aeration process. However, natural aeration is often insufficient to meet the oxygen requirements of intensive or semi-intensive aquaculture ponds, particularly under high stocking densities and elevated feeding rates [5]. Consequently, artificial aerators are widely employed to maintain adequate DO levels, making aeration systems one of the most critical components in aquaculture operations. Commonly used artificial aerators include paddle wheel aerators, diffused aerators, vertical pump aerators, spiral aerators, and propeller aerators [6]. Diffused aerators and vertical pump aerators are typically used in smaller ponds, whereas paddle wheel aerators are the most widely adopted due to their high oxygen transfer efficiency, effective water circulation, ease of installation, low maintenance requirements, and relatively low cost [7].

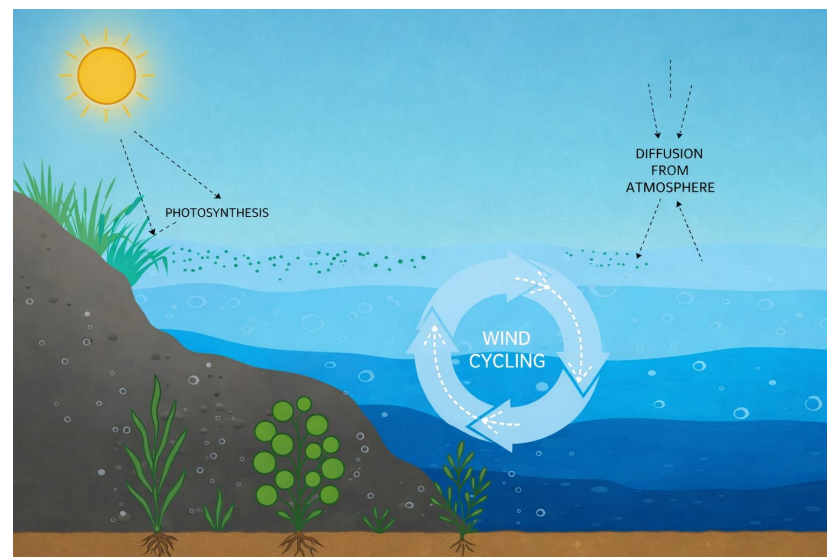


Figure 1. Natural dissolved oxygen in aquatic ecosystem.

Figure 2a shows a two-impeller wheel aerator powered by a 745.6 W (1 hp) electric motor. The water circulation mechanism of a two-impeller paddle wheel aerator, in which water is splashed into the atmosphere to enhance the oxygen absorption, is shown in Figure 2b. The daily energy requirement of one two-impeller paddle wheel aerator is 17.984 kWh. The effectiveness of the aeration is strongly influenced by the pond size and the capacity of the aerators employed [8]. In most commercial aquaculture practices, aerators are operated continuously (24 h a day) throughout the entire production cycle

to maintain an adequate DO level. An increase in both the number and surface area of aquaculture ponds necessitates a corresponding increase in the number and capacity of aerators, resulting in substantially higher energy consumption. In addition to the aerators, aquaculture farms utilise various other electrical loads including freezers and water pumps, feeding systems, monitoring and control systems, and lighting loads, which further contribute to the total energy demand. This highlights the substantial operational energy requirements and associated costs required for the stable and reliable operations of aquaculture farms. Beyond cost considerations, such high energy consumption raises serious concerns regarding environmental sustainability. While aquaculture production plays a critical role in ensuring food security, the associated high energy consumption results in substantial CO₂ emissions, thereby intensifying environmental and climate-related challenges.



Figure 2. (a) Two-impeller wheel aerator; (b) operation of paddle wheel aerator.

The integration of renewable energy systems, particularly solar photovoltaic (PV)-based power systems, for powering aerators or supporting overall farm energy demand is a practical and scalable solution to reduce electricity consumption and operating costs while promoting environmentally sustainable aquaculture practices [8]. The design, operation, performance evaluation, and cost-effectiveness of solar PV-powered aeration systems have been investigated in Thailand, South America, Egypt, the Philippines, Indonesia, India, and other regions [7–10]. A techno-economic and environmental assessment of a grid-connected solar PV system for aeration is presented in [11]. The study aims to optimise the net present cost (NPC), renewable fraction (RF), and CO₂ emission reduction based on assumed operating conditions using bio-inspired optimisation techniques. Although potential cost and emission reductions are demonstrated, the system configuration retains a diesel generator as an auxiliary energy source, thereby constraining the achievable environmental benefits. Furthermore, the results are highly sensitive to assumed load profiles and operational strategies. The techno-economic optimisation of a standalone floating PV (FPV) system with battery energy storage for aquaculture aeration is investigated in [12]. Similarly, a pilot study on the design and performance evaluation of a standalone FPV-powered paddle wheel aerator is reported in [13]. While both studies confirm the technical feasibility of FPV systems for aerator operation, the analysis in [13] considers limited operating hours and relatively low power demand, which does not represent commercial aquaculture practices requiring prolonged or continuous aeration. In addition, long-term operational performance and component degradation effects are not

comprehensively evaluated, and the large battery capacity requirements and high capital cost of standalone FPV systems present challenges for large-scale deployment. In [14], the technical feasibility of an automated aerator powered by a standalone floating PV system is demonstrated through experimental analysis. However, system-level design details and comprehensive techno-economic and environmental evaluations are not addressed. In [15], the optimisation of a PV-powered aerator operation in a shrimp farm in Indonesia is presented for multiple system configurations, including grid-only, on-grid PV, off-grid PV, and hybrid PV systems. Although optimised configurations with reduced electricity costs and CO₂ emissions are identified, the return on investment and life-cycle economic assessments are not reported. Simulation-based analyses of solar PV-powered aerator systems are presented in [10,16], where simplified load assumptions and low-power aerators are employed. Similarly, ref. [17] evaluates hybrid renewable energy integration using PV and wind systems with battery storage for a shrimp farm in Thailand through MATLAB-based simulations. The studies in [10,15–17] are purely simulation-based and rely primarily on assumed or simplified operational data, limiting their applicability to real aquaculture farm conditions. The work presented in [4] focuses on the design and implementation of a semi-floating solar-powered venturi aeration system for aquaculture, with experimental validation of the aeration performance. However, the economic performance indicators and environmental impact metrics are not quantified. A review study in [8] summarises energy efficiency strategies and solar PV integration in aquaculture power systems. Table 1 presents a comparative analysis of the related research works.

Table 1. Comparative study of solar PV powered aerators.

Ref.	Aerator Type and Operation	System Configuration	Method/Tool	Techno-Economic Findings	Environmental Findings	Key Limitations
[11]	Paddlewheel, limited hours	PV + Grid + DG	Multi-objective optimisation (NPC, RF, CO ₂)	✓	✓	Dependency on DG, assumes short aeration duration.
[12]	Low-power aerator, limited hours	Standalone FPV with Battery	Rule-based sizing, simulation studies	✓ Not in detail	x	Low power system, assumes short aeration duration.
[13]	Paddlewheel aerator	Standalone FPV with Battery	Experimental study, HOMER-based Sizing	✓ Not in detail	x	Short term analysis, no quantitative case study.
[14]	Diffused aeration system	Standalone FPV with battery	Experimental study	✓ No life-cycle analysis	x	Short term analysis, no detailed techno-economic and environmental analysis.
[15]	Paddlewheel aerators	Grid/PV, Grid/PV/BESS, and PV/BESS Scenarios	HOMER-based sizing and optimisation	✓ Limited	✓ Limited	Simulation based, aerator operation hours assumed.
[10,16]	Aerator + lighting, limited hours	Standalone PV with Battery	HOMER-based sizing	✓ Cost of electricity analysis only	x	Simulation based, simplified load profile with assumptions.
[17]	Shrimp farm	Grid, PV, Wind, Battery	MATLAB-based optimisation	✓ Life-cycle cost and reliability only	x	Simulation based study with assumptions.
[4]	Venturi aeration system	Standalone PV with Semi-floating Aerator	Experimental study	x	✓ Limited	No techno-economic assessment.
[8]	Aeration and pumping	PV/Hybrid	Review and meta-analysis	Identifies cost drivers (battery, inverter)	Highlights sustainability benefits	No quantitative case study.

The literature reveals that most studies on solar PV-powered aerators are predominantly simulation based, with only a limited number of investigations considering real-time system operation. Many reported studies focus on standalone PV configurations, where battery storage capacity and associated costs remain major limiting factors, particularly for large-scale deployment. In addition, aerator load profiles and operating hours are often assumed or simplified, which restricts the applicability of the findings to actual aquaculture farm conditions. The reviewed studies further indicate that hybrid system architectures and grid-interactive solutions are insufficiently explored, and a systematic evaluation of technical performance, economic viability, and environmental impact across different PV penetration levels is largely absent.

To overcome these limitations, the present work focuses on the planning, optimal sizing, and implementation of a hybrid solar PV system for aerator operation in an operational aquaculture farm. Unlike most existing studies, the analysis is based on measured energy demand and real-time system operation, enabling a realistic assessment of aerator energy requirements and system performance. A comprehensive techno-economic and environmental evaluation is conducted, explicitly accounting for system losses, cost components, and emission reduction potential. Furthermore, the study examines system performance at different PV penetration levels, providing quantitative insights into energy contribution, cost-effectiveness, and environmental benefits under varying levels of solar integration. The proposed methodology is demonstrated through a case study in Brunei Darussalam, and the outcomes offer practical guidance and actionable insights to support informed decision-making and strategic energy planning for sustainable aquaculture development.

2. Methodology

2.1. Aquaculture Farm with Solar PV System for Aerator Operation

Figure 3 shows the aquaculture farm selected for this study, consisting of 14 aquaculture ponds. The farm is located in Kampong Tungku, Brunei Darussalam. The farm cultivates tilapia, prawn, and shrimp. Each pond is equipped with a minimum of two two-propeller paddle wheel aerators, while ponds with larger surface areas, such as ponds 1 and 8, are equipped with four aerators each. During peak production periods, up to 30 aerators may operate simultaneously across the farm.

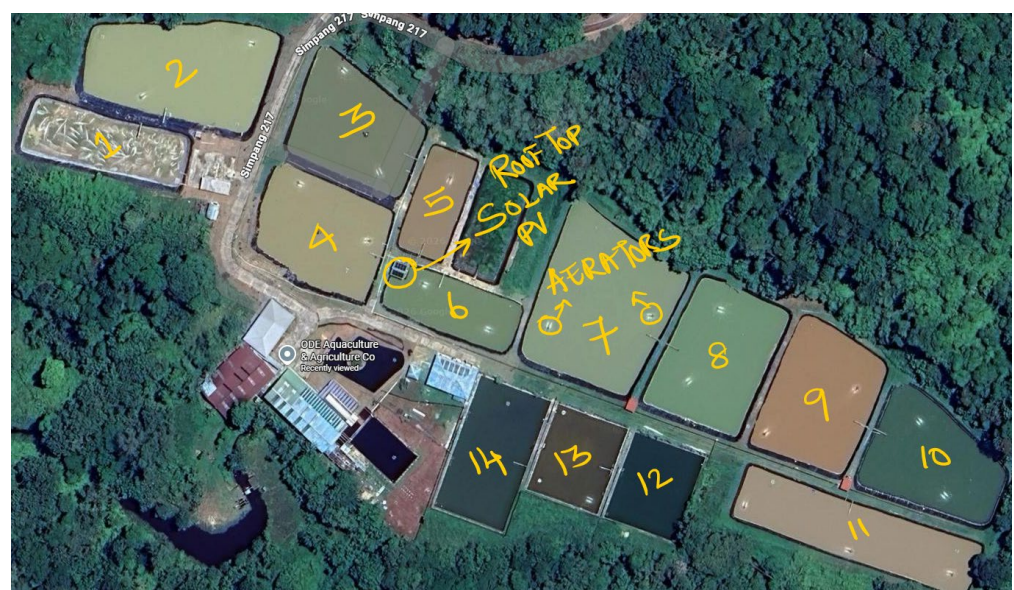


Figure 3. ODE aquaculture farm in Brunei Darussalam (Source: Google Maps).

The daily average energy consumption, monthly energy consumption, and the corresponding minimum and maximum power demand of the selected aquaculture farm are summarised in Table 2. The hourly energy consumption on a representative day in July 2025 and the daily consumption for the month of July 2025 are shown in Figures 4a and 4b, respectively. The farm exhibits a daily energy consumption of 487.53 kWh, resulting in an average monthly energy consumption of 15.11 MWh. The average minimum and maximum power demands are 13.853 kW and 34.225 kW, respectively. These results clearly demonstrate the substantial operational energy requirements of aquaculture farms required to maintain stable and continuous farm operation. Beyond the economic burden associated with electricity consumption, such high energy usage also raises environmental sustainability concerns, particularly due to greenhouse gas emissions associated with conventional grid-based electricity generation.

Table 2. Power and energy demand in aquaculture farm.

	Daily	Monthly
Consumption	487.53 kWh	15.11 MWh
Min. Power	13,853 W	
Max. Power	34,225 W	

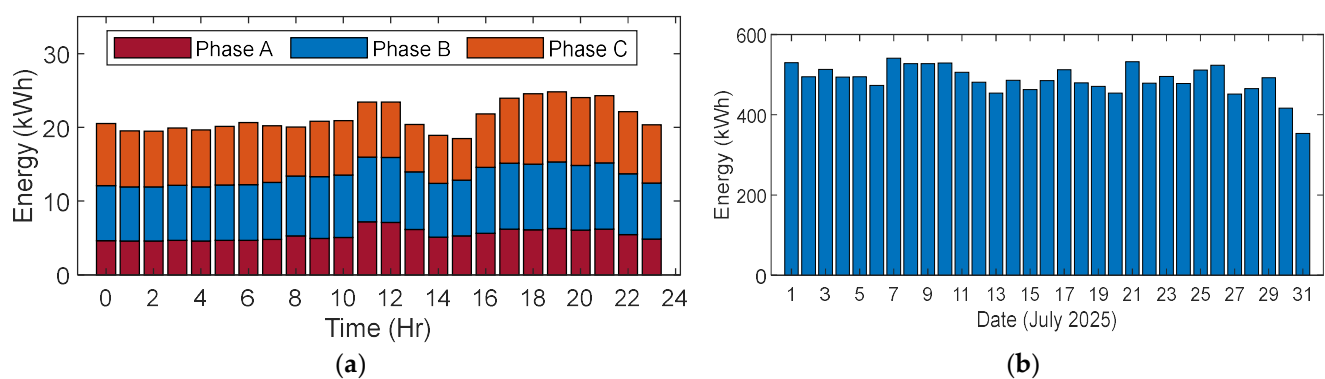


Figure 4. Hourly (18 July 2025) (a) and daily (b) consumption of aquaculture plant (July 2025).

The daily average PV generation potential in Brunei Darussalam ranges from 3.10 to 4.24 kWh/kWp/day, depending on the location, while the average daily generation in most areas of the Bandar region is approximately 4.10 kWh/kWp/day. As discussed earlier, the energy requirement for operating a single paddle wheel aerator is approximately 18 kWh/day. Accordingly, the PV capacity required to operate one aerator entirely using solar-generated electricity can be estimated as

$$\text{PV capacity} = \frac{\text{Total demand in kWh/day}}{\text{Avg. PV generation/day/kWp}} \quad (1)$$

$$\text{PV capacity} = \frac{18 \text{ kWh/day}}{\frac{4.1 \text{ kWh}}{\text{day}}/\text{kWp}} = 4.4 \text{ kWp}.$$

Aerator operations in aquaculture farms are generally continuous throughout the day and characterised by a nearly constant power demand, whereas PV power generation is intermittent and restricted to daylight hours. As previously noted, aerator operation must remain uninterrupted to maintain adequate dissolved oxygen levels. Consequently, a hybrid PV system integrating a solar PV, battery energy storage, and grid connectivity is adopted to (i) ensure uninterrupted power supply to the aerators, (ii) store excess PV

generation, and (iii) export surplus energy to the grid, while importing power during generation deficits.

The proposed hybrid PV system for aerator operation is illustrated in Figure 5. The PV system consists of a 4.64 kWp PV array, formed by eight (8) series-connected 580 Wp PV modules, interfaced with a 5 kW hybrid solar inverter. Energy storage is provided by a 24 kWh battery bank, comprising eight 12 V, 250 Ah lithium-ion batteries. The PV system is connected to the utility grid, and the aerators are supplied through the hybrid inverter, enabling flexible power exchange between the PV array, battery storage, grid, and loads.

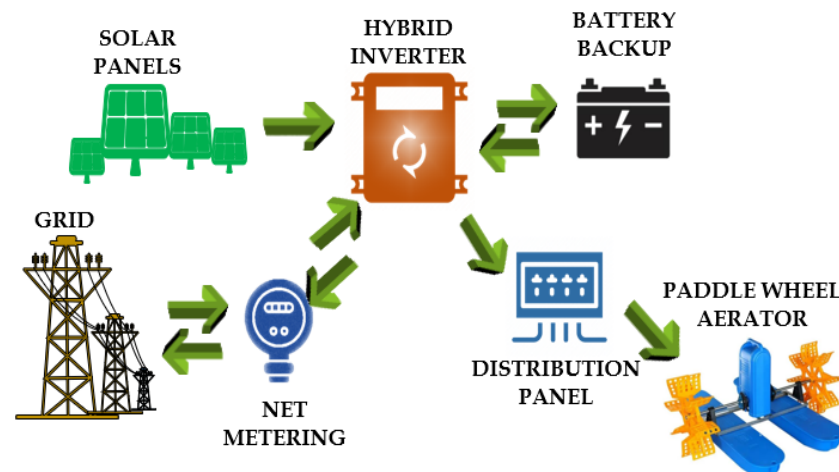


Figure 5. Hybrid PV system for aerator operation in aquaculture farm.

The installed hybrid PV system, along with the weather monitoring station and data acquisition system used for real-time performance monitoring, is shown in Figure 6.



Figure 6. Hybrid PV system: (a) PV array, (b) weather monitoring station, (c) battery storage, (d) hybrid inverter.

2.2. Technical Analysis of Solar PV System

The technical analysis of the proposed PV system is conducted following the methodology prescribed in [18]. The daily PV yield represents the normalised energy output of the PV system and is defined as the ratio of the daily AC energy output of the system ($E_{(AC,day)}$) to the rated capacity of the installed PV system ($P_{pv(rated)}$).

$$Y_{(AC,day)} = E_{(AC,day)} / P_{PV(rated)} \quad (2)$$

The monthly yield or the yield over a specified number of days (N) is obtained as

$$Y_{(AC,N)} = \sum_{d=1}^N Y_{(AC,day)}. \quad (3)$$

The reference yield of the system Y_{ref} is defined as

$$Y_{ref} = G_i / G_{STC}, \quad (4)$$

where G_i is the average daily global horizontal irradiation at the site, and G_{STC} is the irradiation under standard test conditions (1000 W/m^2). The performance ratio (PR) of the PV system (R_p) is calculated using

$$R_p = Y_{AC} / Y_{ref}. \quad (5)$$

The average daily global horizontal irradiation (GHI) in Brunei's Muara district is reported as $5.25 \text{ kWh/m}^2/\text{day}$ [19]. Accordingly, the reference yield of the PV system is

$$Y_{ref} = 5.25 \text{ kWh/kWp/day}.$$

The overall efficiency of the PV system depends on the AC output, average solar irradiation at the site, and the total active area of the PV modules (A). The system efficiency is evaluated using Equation (6), expressed as

$$\eta = \frac{E_{AC}}{G_i * A}. \quad (6)$$

Jinko Solar 580 Wp Monocrystalline Silicon PV Modules are used in the proposed system. The conversion efficiency of the selected PV module is 22.45%, and the area of one PV module is 2.58 m^2 . The installed system has eight PV modules, resulting in a total active PV area (A) of 20.66 m^2 . Table 3 summarises the performance analysis of the PV system based on the real-time PV system power generation data.

The average daily PV potential at the selected site is 4.10 kWh/kWp/day [19], while the measured daily system yield ($Y_{(AC,day)}$) is 3.98 kWh/kWp/day . According to IEC 61724, the PV system's performance is considered satisfactory when the performance ratio is between 0.75 and 0.85 [20]. For the system under study, the calculated overall PR is 0.76, confirming the acceptable system performance under real operating conditions. This value is consistent with performance ratios reported for grid-connected PV systems operating in tropical climates, where PR values typically range between 0.7 and 0.8 due to elevated temperature and humidity effects [21]. Furthermore, the observed overall system efficiency of 72.65% is consistent with the IEC-reported field performance for the PV systems installed in tropical regions when temperature effects, inverter losses, and balance-of-system losses are taken into account.

Table 3. Performance analysis of 4.64 kWp PV system.

Month and Year	$Y_{(AC,N)}$ (4.64 kWp)	$Y_{(AC,day)}$ (kWh/kWp)	R_p	η (%)
November 2024	565.77	4.06	0.77	74.21
December 2024	518.00	3.60	0.69	65.76
January 2025	515.90	3.59	0.68	65.49
February 2025	463.80	3.57	0.68	65.18
March 2025	566.30	3.94	0.75	71.89
April 2025	557.17	4.02	0.76	73.09
May 2025	608.20	4.23	0.81	77.21
June 2025	613.56	4.41	0.84	80.48
July 2025	634.70	4.41	0.84	80.57
Average	560.38	3.98	0.76	72.65

3. Results and Discussion

3.1. Economic Assessment

This section presents the operational studies conducted at the aquaculture farm equipped with the installed hybrid PV system under different operating scenarios. Initially, one aerator was connected to the hybrid inverter, and the system was configured such that the battery storage was utilised only during emergency conditions, such as grid outages.

Figure 7a shows the PV power generation, aerator power consumption, grid power exchange, and battery state of charge (SoC) for Scenario 1 on a representative day (4 December 2024). The aerator is fully supplied by the grid prior to the onset of PV generation. Once PV generation commences, the aerator power demand is shared between the PV system and the grid, depending on the instantaneous PV output. When the PV generation exceeds the load demand, excess energy is exported to the grid. Under this configuration, the backup battery system is not utilised for load supply. Operational observations also indicate that the inverter has sufficient capacity to supply more than one aerator.

Based on this observation, a second aerator was connected to the inverter, and the system settings were modified to allow battery discharge between 19:00 and 06:00 (next day). This configuration enables a more effective utilisation of PV-generated energy and stored battery energy. The PV power generation, aerator power consumption, grid power exchange, and battery SoC for Scenario 2 on a representative day (26 July 2025) are shown in Figure 7b. As expected, the total demand increases due to the additional aerator. The battery begins discharging at 01:00, supplying a constant portion of the load, while the remaining demand is met by the grid. The battery discharge stops at 06:00, after which the total load demand is supplied solely by the grid until PV generation resumes.

Subsequently, the PV-generated power supplies the load and charges the battery. By 09:35, the PV generation exceeds both the load demand and battery charging power, resulting in the export of surplus power to the grid, indicated by negative grid power. The battery reaches a full state of charge at 12:30, at which point a noticeable increase in grid export is observed. Until 16:15, the load demand is met entirely by PV generation, with surplus energy exported to the grid. Beyond this time, the load is supplied jointly by PV generation and grid power. At 19:00, the battery resumes constant-power discharge and continues supplying energy until 06:00 the following day, subject to the defined operational constraints.

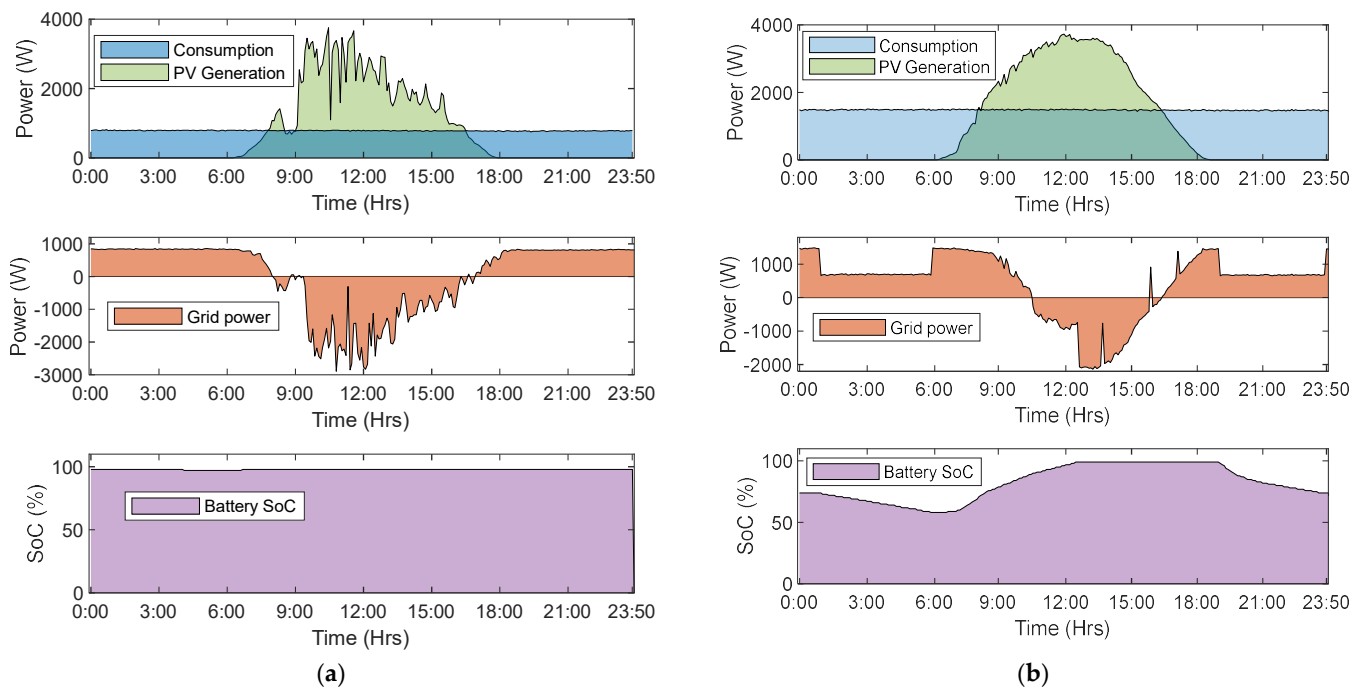


Figure 7. PV generation, power consumption, grid power, and battery SoC for (a) Scenario 1 and (b) Scenario 2.

The daily energy distribution, including the total PV generation, total consumption, grid import and export, and battery charging and discharging energies for both scenarios, is summarised in Table 4. Under Scenario 1, the battery charging and discharging energies are 300 Wh and 500 Wh, respectively, representing internal self-consumption rather than direct load supply. Analysis of the PV generation, grid feed-in, and self-utilisation ratio indicates that more than 50% of the generated energy is exported to the grid. In contrast, under Scenario 2, the addition of a second aerator and the revised battery dispatch strategy increase PV self-utilisation to 79.4% on the selected day. This results in a substantial reduction in grid feed-in and more effective on-site utilisation of PV-generated energy.

Table 4. Load consumption and distribution of energy between the sources.

Production (kWh)	Consumption (kWh)	Feed-in Power (kWh)	Energy Purchased (kWh)	Energy Charged (kWh)	Energy Discharged (kWh)	Self-Used Ratio (%)
18	16.3	9.6	11.3	0.3	0.5	46.6
24.8	31.9	5.1	16.1	8.1	7.4	79.4

The daily average production and consumption for January 2025 and February 2025 are presented in Figures 8a and 8b, respectively. The system was operated with one aerator from 9 January 2025 to 4 February 2025, and the second aerator was added to the system on 5 February 2025. As a result, the daily average energy consumption increased from 15.6 kWh/day to 31.2 kWh/day, reflecting the proportional increase in load demand due to the addition of the second aerator.

The monthly PV production, energy consumption, grid power including feed-in and energy import from the grid, battery charging and discharging, and the PV self-used ratio from November 2024 to July 2025 is summarised in Table 5. The monthly energy distribution between the subsystems for both PV generation and energy consumption are illustrated in Figures 9 and 10, respectively.

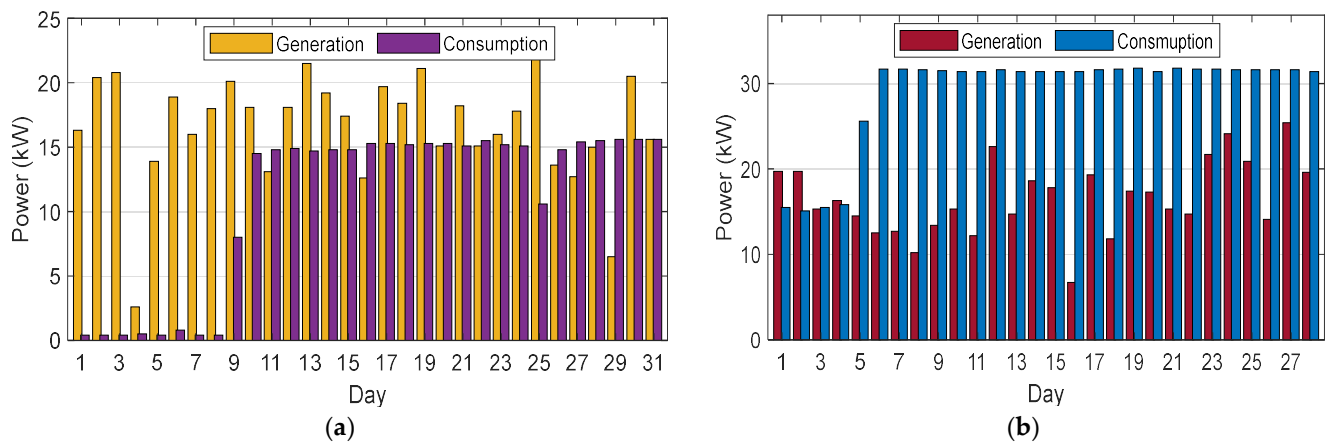


Figure 8. Daily PV generation and consumption during (a) January 2025 and (b) February 2025.

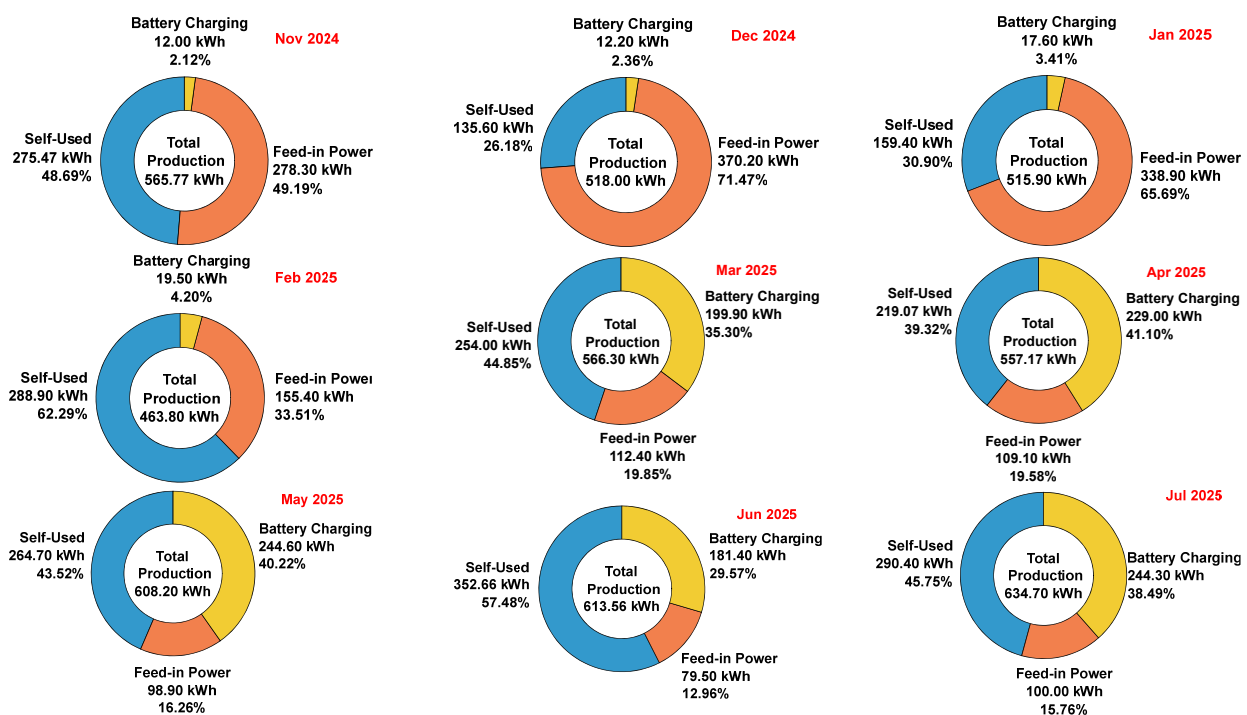


Figure 9. Distribution of monthly PV generation.

The results indicate that PV generation is utilised to meet the load demand, excess generation is fed into the grid, and a portion of energy is stored in the battery storage system. As mentioned previously, the battery was configured as an emergency backup until February 2025, with battery charging and discharging accounting for only 2–4% of the total energy flow. To improve the system utilisation, the operation strategy was revised from March 2025 to allow controlled battery discharge during night-time operation, enabling the battery to be fully recharged from PV generation during the daytime. This adjustment resulted in a marked increase in the battery charging and discharging activity, leading to a significant improvement in PV self-utilisation and a reduction in grid export. The grid import and export profiles reflect the dynamic power exchange between the grid and the load, which varies with aerator operation. During March 2025, May 2025, and July 2025, the total monthly energy consumption reached 983.10 kWh, 977.70 kWh, and 990.70 kWh, respectively, indicating that two aerators were in continuous operation during these months. These observations further confirm the high and sustained energy demand of aquaculture farms during full production cycles.

Table 5. Monthly generation and consumption analysis.

Month	Total Production (kWh)	Battery Charging (kWh)	Total Self Usage (kWh)	Feed-in Energy (kWh)	Total Consumption (kWh)	From Production (kWh)	Grid Consumption (kWh)	Energy Discharged (kWh)	Self-Used Ratio (%)
November 2024	565.77	12.00	287.47	278.30	456.20	124.6	315.8	15.80	50.81
December 2024	518.00	12.20	147.8	370.20	254.10	57	182.4	14.70	28.53
January 2025	515.90	17.60	177	338.90	340.50	93.3	231.7	15.50	34.31
February 2025	463.80	19.50	308.4	155.40	813.00	212.5	583.8	16.70	66.49
March 2025	566.30	199.90	453.9	112.40	983.10	170	608.8	204.30	80.15
April 2025	557.17	229.00	448.07	109.10	777.50	119.5	439.7	218.30	80.42
May 2025	608.20	244.60	509.3	98.90	977.70	185.7	562.6	229.40	83.74
June 2025	613.56	181.40	534.06	79.50	740.00	142.9	423.4	173.70	87.04
July 2025	634.70	244.30	534.7	100.00	990.70	190.1	569.4	231.20	84.24

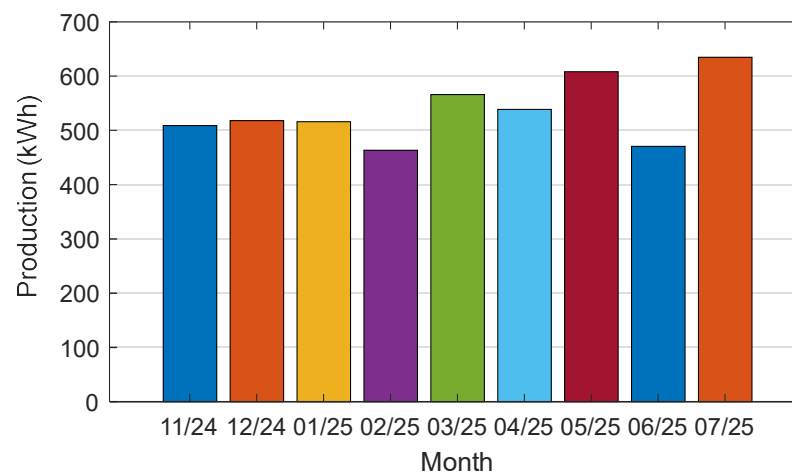
**Figure 10.** Distribution of monthly consumption.

A quantitative comparison of the PV self-utilisation, based on measured operational data, is summarised in Table 6. The results demonstrate that Scenario 2 increased the average PV self-utilisation from approximately 45% to over 83%, while substantially reducing the grid export, under the continuous operation of two aerators in real aquaculture farm conditions.

The monthly PV production is shown in Figure 11. Based on the available data, the average monthly PV generation is 560.38 kWh, and the average monthly energy consumption of the aquaculture farm is 15.03 MWh. The installed PV system contributes approximately 3.7% of the total daily energy consumption, which is a relatively small share of PV generation compared to the overall energy demand of the farm during full-scale operation.

Table 6. Quantitative comparison of PV self-utilisation under different battery operation scenarios.

Parameter	Scenario 1	Scenario 2
Battery operation mode	Emergency backup only	Active energy management (Night discharge)
Battery charging energy	12–19 kWh/month	181–245 kWh/month
Battery discharging energy	14.7–16.7 kWh/month	173.7–231.2 kWh/month
Average PV self-usage ratio	≈45.0%	≈83.1%
PV self-usage range	28.5–66.5%	80.1–87.0%
Grid export	High (155–370 kWh/month)	Significantly reduced (79–112 kWh/month)
Aerator operation	One aerator	Two aerators (continuous operation)

**Figure 11.** Monthly PV generation.

3.2. Cost Analysis

In Brunei Darussalam, the utility grid is highly reliable, and the probability of power outages is minimal. However, aquaculture farms require a continuous and uninterruptible power supply, as the survival and growth of aquatic animals depend primarily on aerator operation and other artificial oxygenation systems. Consequently, emergency backup generators are installed at aquaculture farms and can come online within a few minutes in the event of power outages or emergency shutdowns. Considering the high reliability of the utility grid and the availability of backup generators, battery storage is not mandatory for solar PV system integration in aquaculture farms in Brunei Darussalam. Accordingly, the cost analysis in this study is performed for an on-grid PV system. The installed 4.64 kW PV system is used as a benchmark, and the analysis is extended to evaluate different PV penetration levels.

The capital cost breakdown of a 4.64 kW on-grid PV system in Brunei Darussalam is presented in Table 7. The miscellaneous costs include the cost of cables, circuit breakers, earthing and the cost other electrical accessories required for the installation.

The total cost of the system, known as the capital cost of the PV system, is calculated using the equation below.

$$CC_{pv} = C_{pv} + C_{inv} + C_{str} + C_{ins} + C_{misc} \quad (7)$$

Considering the size of the system, the annual maintenance cost is taken as 1% of the system cost, which is obtained using

$$C_m = CC_{pv} \times 0.01. \quad (8)$$

Table 7. Cost of solar PV system components.

Item	Cost (in BND)
Solar Panels (C_{pv})	1600.00
Inverter (C_{inv})	1000.00
Mounting Accessories (C_{str})	500.00
Installation (C_{ins})	500.00
Miscellaneous Costs (C_{misc})	500.00

The lifetime of the PV system is considered as 25 years. The depreciation and floating rate are not considered in this study. The lifetime of on-grid inverters is typically 15–20 years. Hence, one inverter replacement is assumed during the lifetime of the PV system. Thus, the lifetime cost of system including the replacement cost ($C_{re(inv)}$) is

$$LC_{sys} = CC_{pv} + C_m + C_{re(inv)}. \quad (9)$$

The capital cost of a 4.64 kW on-grid PV system (CC_{pv}) is BND 4100.00, and the maintenance cost C_m is BND 1025.00. Therefore, the lifetime system cost (LC_{sys}) is BND 5625.00, including the inverter replacement cost of BND 500.00.

As stated earlier, the average monthly production of the PV system is 560.38 kWh. Therefore, the lifetime energy generation of the PV system is 168.11 MWh. The annual derating factor of the selected panels is 0.4% per year. Therefore, the adjusted lifetime generation of the system LG_{Energy} is 160.29 MWh. Thus, the levelised cost of electricity is

$$LCoE = \frac{LC_{sys}}{LG_{Energy}} = 0.035 \text{BND/kWh}. \quad (10)$$

The average monthly electricity consumption of the selected aquaculture farm is approximately 15 MWh. The peak demand varies between 25 kW and 35 kW with an average peak demand of 30 kW. The average monthly electricity bill of the farm is BND 1900.00. According to the commercial electricity tariff in Brunei Darussalam [20], the per unit energy cost for the aquaculture farm is BND 0.126/kWh (approximately 12.5 cents/kWh). A comparison of these costs shows that the LCoE of PV generated energy is much cheaper than the cost of electricity purchased from the utility services. This confirms the potential cost savings with PV system integration in an aquaculture farm.

In Brunei Darussalam, a one-one credit scheme is followed, whereby the excess electricity generated by solar PV system is offset against the grid consumption at the same tariff rate. Therefore, the cost of PV generated electricity is also BND 0.126/kWh. The average monthly cost of the PV generated energy can be calculated using

$$EC_{pv} = COE \times E_{PV}. \quad (11)$$

For an average monthly PV generation of 560.38 kWh, the monthly savings amounts to BND 70.67, resulting in annual savings ($ESC_{pv(year)}$) of BND 848.04. The lifetime energy savings cost ($LESC_{pv}$) is estimated as

$$LESC_{pv} = ESC_{pv} \times Lifetime_{pv}. \quad (12)$$

This yields a total lifetime energy savings cost of BND 21,201.00 over the 25-year system lifetime. The return of investment (ROI) and the payback period (PB) are calculated as follows:

$$ROI = \frac{LESC_{pv} - LC_{sys}}{CC_{pv}} = 3.79\%, \quad (13)$$

$$PB = \frac{LC_{sys}}{ESC_{pv(year)}}. \quad (14)$$

The calculated ROI is 3.79%, and the payback period is 6.63 years (6 years and 8 months). The total cost savings over the lifetime achieved through PV system integration is obtained using Equation (15):

$$CS_{total} = LES C_{pv} - LC_{sys}. \quad (15)$$

The total lifetime cost savings for the 4.64 kWp PV system is BND 15,576.00.

3.3. Basic Sensitivity Analysis

In this section, a basic sensitivity analysis of the key economic parameters (capital cost, electricity tariff) is presented. The base values of the capital cost, electricity tariff, and payback period are BND 4100.00, BND 0.035, and 6.63 years, respectively. For the analysis of the capital cost and electricity tariff, $\pm 20\%$ variation is considered. While Figure 12A illustrates the sensitivity of the LCOE and PB to capital cost, Figure 12B shows the sensitivity of the annual savings and PB to the electricity tariff. For the selected range of variability, the levelised cost of energy is obtained between BND 0.028 and 0.042/kWh, and the payback period changed from approximately 5.5 to 8.0 years. On the other hand, with a $\pm 20\%$ change in electricity tariff, the annual savings have a wider variation from approximately BND 678.00 to BND 1017.00, and the payback period changes from approximately 8.3 years to 5.5 years.

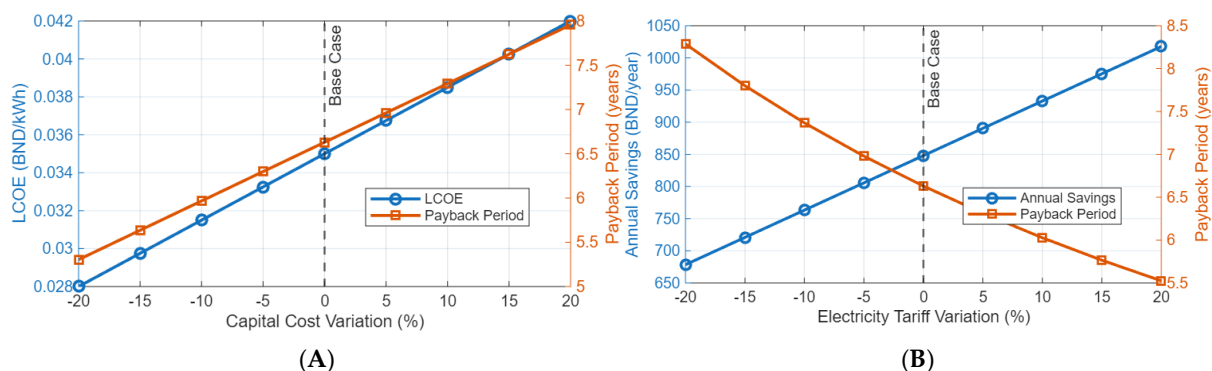


Figure 12. (A). Sensitivity of annual savings and payback period to electricity tariff. (B). Sensitivity of annual savings and payback period to electricity tariff.

3.4. Cost Analysis Under Different PV Penetration Levels

The analysis is carried out further to evaluate the costs under the PV penetration level of 10% of the total consumption of the farm, which is 12.16 kWp, 25% (30.40 kWp), and 50% (60.81 kWp). The system cost, lifetime PV generation, LCOE, ROI, and PB period under the selected conditions are presented in Table 8.

Figure 13 shows the comparison between the LCoE, ROI, PB, and lifetime cost savings at different penetration levels of PV systems. The results indicate that, as the system size increases, the LCoE decreases, which results in an increased ROI and shorter payback period. The payback period decreased from 8.32 years for the 12.1 kWp system to 6.9 years for the 60.8 kWp system. In addition, the total lifetime cost savings increase substantially

with higher PV penetration, reaching over BND 200,000 for the 50% penetration scenario. These findings demonstrate that the integration of higher capacity PV systems offers potential long-term energy savings and cost savings for aquaculture farms. The environmental assessment is presented in the following subsection.

Table 8. Cost comparison summary under different PV penetration levels.

PV Penetration Level (%)	10%	25%	50%
PV Capacity (kW _p)	12.16	30.41	60.82
Capital Cost	13,200.00	28,000.00	55,000.00
Maintenance Cost	3300.00	7000.00	13,750.00
Replacement Cost	2000.00	5000.00	8000.00
Total Cost	18,500.00	40,000.00	76,750.00
Production/month (kWh)	1468.87	3672.18	7344.37
Lifetime Production (MWh)	440.66	1101.66	2203.31
LCoE	0.042	0.036	0.035
LESC _{pv}	55,523.4	138,808.5	277,617.1
ROI (%)	2.80	3.53	3.65
PB (years)	8.33	7.20	6.91
Lifetime Cost Savings	37,023.41	98,808.53	200,867.10
All costs in BND			

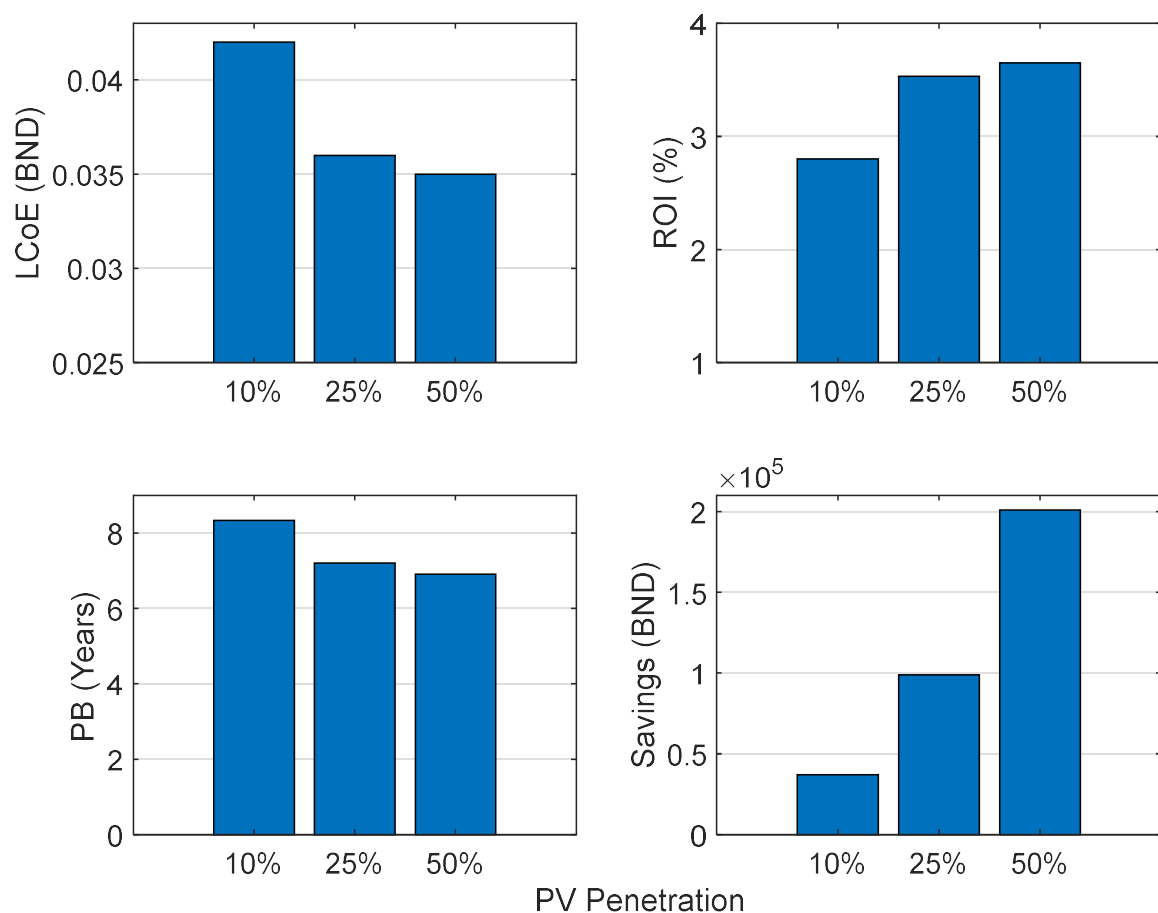


Figure 13. Economic assessment.

3.5. DCF-Based Sensitivity Analysis of ROI and Payback Period

To evaluate the robustness of the economic performance, a discounted cash flow (DCF)-based sensitivity analysis is conducted by assuming a discount rate of 5%. The annual energy cost savings from the PV system are BND 848.04, and the lifetime of the PV system is 25 years. The present value of lifetime energy savings is calculated as

$$PV_{\text{savings}} = 848.04 \times \frac{1 - (1 + 0.05)^{-25}}{0.05} = \text{BND } 11,945.6.$$

Then, the DCF-based return on investment (ROI_{DCF}) is obtained using Equation (16), as follows:

$$ROI_{DCF} = \frac{PV_{\text{savings}} - LC_{\text{sys}}}{CC_{\text{pv}}}, \quad (16)$$

$$ROI_{DCF} = \frac{11,945.6 - 5625}{4100} = 1.54 \text{ (or 154\%)}. \quad (16)$$

In addition, the discounted payback period (DPB) is determined by accumulating the discounted annual savings until they equal the lifetime system cost ($LC_{\text{sys}} = \text{BND } 5625$). The cumulative discounted savings exceeded the investment during the ninth year. Thus, the DCF-based payback period is approximately 9 years.

3.6. Environmental Assessment

In Brunei Darussalam, approximately 98% of the electricity generation is derived from coal, oil, and natural gas [22], and the carbon emission, K_i , is estimated as 0.85 kg/kWh [23]. The monthly carbon emissions due to the total electricity consumption in the aquaculture farm, CE_L , is estimated using Equation (17), and the monthly the carbon emissions reduction due to PV production, $CE_{LESS, PV}$, is calculated using Equation (18).

$$CE_L = K_i \times P_{L,m} \quad (17)$$

$$CE_{LESS, PV} = K_i \times Y_{pv,m} \quad (18)$$

The daily average CO₂ emission of the aquaculture farm is 425.8956 kgCO₂ resulting in a monthly average CO₂ emission (CE_L) of 12,776.87 kgCO₂. The currently installed PV system reduces 476.8956 kgCO₂ per month and 142.896 tonnes of CO₂ emission over its lifetime of 25 years. Table 9 presents the CO₂ emission reduction with the integration of the PV system into the farm at different penetration levels. The currently installed system can reduce only 3.7% CO₂ emission over the present electricity consumption rate. However, increasing the PV penetration significantly enhances the environmental benefits. A 60.82 kW_p PV system reduces 50% of CO₂ emission, with a monthly reduction of 6.24 tonnes of CO₂. The lifetime reduction in CO₂ emission would be 1872.81 tonnes.

Table 9. Emission reduction analysis under different PV penetration levels.

PV Penetration Level	10%	25%	50%
PV Capacity (kW _p)	12.16	30.41	60.82
Production/month (kWh)	1468.873291	3672.183	7344.366
Monthly CO ₂ emission reduction (tonnes)	1.25	3.12	6.24
Lifetime Production (MWh)	440.66	1101.66	2203.31
Lifetime CO ₂ emission reduction (kilotonnes)	374.56	936.41	1872.81

These results show that solar PV integration in aquaculture farms not only delivers economic benefits but also contributes substantially to carbon emission mitigation, supporting long term environmental sustainability and climate resilient food production.

This study provides a techno-economic and environmental assessment of PV-integrated aquaculture systems, based on a deployed roof top PV system operation and real-time operational energy consumption data of the farm and particularly aerator operation. Likewise, the environmental assessment in this study considers only operational CO₂ emission reductions resulting from the displacement of grid electricity by solar PV generation. Emissions associated with the life-cycle stages of PV systems, including manufacturing, installation, and end-of-life management, are not considered. Incorporating intelligent aeration control, floating PV deployment, and life-cycle sustainability analysis are identified as areas for future work.

4. Conclusions

This paper evaluated the technical, economic, and environmental benefits of the PV system integration into an aquaculture farm in Brunei Darussalam. The energy consumption profile of the selected farm and the energy demand for aerator operation were analysed. The case studies conducted in an aquaculture farm with the installation of a 4.64 kWp hybrid PV system for aerator operation under different scenarios are explained in detail. The technical evaluation of the PV system is carried out, and the economic and environmental assessment of the PV systems at different penetration levels and their benefits are analysed and discussed. The findings of the studies highlight the higher energy demand of the aquaculture industry and the benefits of PV system integration into its energy mix. The monthly average energy consumption in the selected farm is 15.1 MWh. With a 61 kWp PV system, 50% of the energy demand in the selected site can be met. At an LCoE of BND 0.035/kWh against the commercial tariff of BND 0.12 per kWh, the system reduces 72% of the electricity cost. With a 3.65% ROI, the investment can be repaid in 6.91 years, and the PV system offers lifetime savings of BND 200,867.05. In addition to the financial benefits, 6.24 tonnes of CO₂ emissions are reduced per month, and the lifetime CO₂ emission reduction with 50% penetration of a PV system is 1872.81 kilotonnes. Overall, the integration of solar PV systems in aquaculture farms directly supports Sustainable Development Goals SDG 7, SDG 12, and SDG 13.

The PV system used in this study is a rooftop system, and the aerator operation is continuous. Future work will focus on the development of an automated control system for aerator operation based on the real-time DO level monitoring of the aquaculture ponds and deployment of a floating PV (Floatovoltaic or Aquavoltaic) system in the plant. The studies reveal that such systems not only enhance the generation efficiency of PV panels but also help to improve the growth and health of aquatic species. Likewise, monitoring the DO level in the aquaculture ponds and the integration of a DO-level based automated control system for aerator operations can reduce the overall energy consumption in the aquaculture farm by 30–40% and thus improve the sustainability and energy efficiency of aquaculture operations.

Author Contributions: Conceptualization, S.M.S. and T.H.L.; Methodology, S.M.S., T.H.L., B.S.R., V.R.P. and S.S.B.; Software, S.M.S.; Validation, S.M.S. and S.S.B.; Formal analysis, S.M.S., T.H.L., B.S.R., V.R.P. and S.S.B.; Investigation, S.M.S.; Resources, S.M.S. and N.A.-Z.T.; Data curation, N.A.-Z.T.; Writing—original draft, S.M.S.; Writing—review & editing, T.H.L., N.A.-Z.T., B.S.R., V.R.P. and S.S.B.; Supervision, S.M.S.; Project administration, S.M.S. and T.H.L.; Funding acquisition, T.H.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Universiti Teknologi Brunei, and the publication was financially supported by the UTB ASEAN Blue Economy Challenge Grant (reference: ASEAN BLUE ECONOMY/IC/UNDP/IX/2024).

Institutional Review Board Statement: Not Applicable.

Informed Consent Statement: Not Applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: Authors would like to thank Universiti Teknologi Brunei for the funding and resources provided to conduct the research. Authors would also like to thank ODE Aquaculture Sdn Bhd, Brunei Darussalam for the facilities offered to conduct the research.

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

References

1. Food and Agriculture Organization of the United Nations (FAO). *In Brief to the State of World Fisheries and Aquaculture 2024: Blue Transformation in Action*; FAO: Rome, Italy, 2024. [\[CrossRef\]](#)
2. Marsal, C.J.; Jamaludin, M.H.; Anwari, A.S.; Chowdhury, A.J.K. The potential of aquaculture development in Brunei Darussalam. *Agric. Rep.* **2023**, *2*, 12–21.
3. Nguyen, N.T.; Matsushashi, R.; Vo, T.T.B.C. A design on sustainable hybrid energy systems by multi-objective optimization for the aquaculture industry. *Renew. Energy* **2021**, *163*, 1878–1894. [\[CrossRef\]](#)
4. Dayioğlu, M.A. Experimental study on design and operational performance of a solar-powered venturi aeration system developed for aquaculture—A semi-floating prototype. *Aquac. Eng.* **2022**, *98*, 102255. [\[CrossRef\]](#)
5. Beg, M.M.; Roy, S.M.; Ramesh, P.; Moulick, S.; Tiyyasha, T.; Bhagat, S.K.; Abdelrahman, H.A. Organic aquaculture regulation, production, and marketing: Current status, issues, and future prospects—A systematic review. *Aquac. Res.* **2024**, *2024*, 5521188. [\[CrossRef\]](#)
6. Roy, S.M.; P, J.; Machavaram, R.; Pareek, C.M.; Mal, B.C. Diversified aeration facilities for effective aquaculture systems—A comprehensive review. *Aquac. Int.* **2021**, *29*, 1181–1217. [\[CrossRef\]](#)
7. Roy, S.M.; Beg, M.M.; Tiyyasha, T.; Bhagat, S.K.; Kim, T.; Pareek, C.M.; Kumar, V.; Kumar, R.; Abdelrahman, H.A. Cost-effective aeration solutions for aquaculture: A study on paddle wheel and spiral aerators. *Aquac. Int.* **2025**, *33*, 327. [\[CrossRef\]](#)
8. Vo, T.T.E.; Ko, H.; Huh, J.-H.; Park, N. Overview of solar energy for aquaculture: The potential and future trends. *Energies* **2021**, *14*, 6923. [\[CrossRef\]](#)
9. Pratama, E.G.; Sunanda, W.; Gusa, R.F. A floating photovoltaic system for fishery aeration. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *926*, 012014. [\[CrossRef\]](#)
10. Prasetyaningsari, I.; Setiawan, A.; Setiawan, A.A. Design optimization of a solar-powered aeration system for fishponds in Sleman Regency, Yogyakarta using HOMER software. In Proceedings of the International Conference on Sustainable Energy Engineering and Application (ICSEEA 2012), Yogyakarta, Indonesia, 6–8 November 2012.
11. Aripriharta, A.; Sukma Adji, A.W.; Bagaskoro, M.C. Techno-economic feasibility: Planning an on-grid solar power system for shrimp pond aeration. *Appl. Sci. Eng. Prog.* **2025**, *18*, 7616. [\[CrossRef\]](#)
12. Jamroen, C. Optimal techno-economic sizing of a standalone floating photovoltaic/battery energy storage system to power an aquaculture aeration and monitoring system. *Sustain. Energy Technol. Assess.* **2022**, *50*, 101862. [\[CrossRef\]](#)
13. Jamroen, C.; Kotchprapa, P.; Chotchuang, S.; Phoket, R.; Vongkoon, P. Design and performance analysis of a standalone floating photovoltaic/battery energy-powered paddlewheel aerator. *Energy Rep.* **2023**, *9*, 539–548. [\[CrossRef\]](#)
14. Borres, E.C.; Sayco, T.B.; Espino, A.N.; Sacdalan, J.C. Design and automation of a solar-powered floating-type aeration system (SPFTAS) for fishponds. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *301*, 012004. [\[CrossRef\]](#)
15. Fikriyadi, Z.A.; Nafiah, R.; Utami, D.M.P. Optimisation of solar-powered aerators for shrimp aquaculture. *IOP Conf. Ser. Earth Environ. Sci.* **2025**, *1488*, 012131. [\[CrossRef\]](#)
16. Chowdhury, T.; Chowdhury, H.; Chowdhury, P.; Hasnat, A.; Barua, B.; Islam, R. Analysis of a solar PV system for aeration systems in aquaculture. In Proceedings of the International Conference on Mechanical, Industrial and Energy Engineering (ICMIEE 2018), Khulna, Bangladesh, 23–24 December 2018.
17. Nookuea, W.; Campana, P.E.; Yan, J. Evaluation of solar PV and wind alternatives for self-renewable energy supply: A case study of shrimp cultivation. *Energy Procedia* **2016**, *88*, 462–469. [\[CrossRef\]](#)

18. Sulthan, S.M.; Peng, A.S.; Norfauzi, M.; Revathi, B.S. Techno-economic feasibility and environmental assessment of a grid-connected PV system for EV charging in Brunei Darussalam. In Proceedings of the 5th International Conference on Innovative Research in Applied Science, Engineering and Technology (IRASET 2025), Fez, Morocco, 15–16 May 2025; pp. 1–6.
19. Solargis. Data, Software and Services for Solar Projects. Available online: <https://solargis.com> (accessed on 9 October 2025).
20. International Electrotechnical Commission (IEC). *Photovoltaic System Performance—Part 1: Monitoring*; IEC 61724-1:2017; IEC: Geneva, Switzerland, 2017. Available online: <https://www.iec.ch> (accessed on 10 January 2026).
21. Marion, B.; Adelstein, J.; Boyle, K.; Hayden, H.; Hammond, B.; Fletcher, T.; Canada, B.; Narang, D.; Shugar, D.; Wenger, H.; et al. Performance parameters for grid-connected PV systems. In Proceedings of the 31st IEEE Photovoltaic Specialists Conference, Lake Buena Vista, FL, USA, 3–7 January 2005; pp. 1601–1606.
22. International Energy Agency (IEA). *Southeast Asia Energy Outlook 2024*; IEA: Paris, France, 2024. Available online: <https://www.iea.org> (accessed on 9 October 2025).
23. Guidi, G.; Violante, A.C.; De Iuliis, S. Environmental impact of electricity generation technologies: A comparison between conventional, nuclear, and renewable technologies. *Energies* **2023**, *16*, 7847. [CrossRef]

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