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DESIGN AND PERFORMANCE ANALYSIS OF AN OFF-GRID PHOTOVOLTAIC SYSTEM FOR AQUACULTURE PONDS IN BORI APPAKAH

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Abstract
The demand for electrical energy in aquaculture, particularly in Pangkep Regency, continues to increase due to the need for nighttime illumination to ensure security and maintain fish activity. However, the geographical location of fish ponds, which are often situated far from the state electricity grid (PLN), creates a significant energy supply challenge. This study aims to design, construct, and analyze the performance of a standalone (off-grid) Photovoltaic (PV) system to supply electrical energy to a 4000 m² fish pond located in Bori Appakah Village. The research methodology includes site assessment, mathematical sizing of system components, system assembly, PVsyst 7.4.8 simulation, and empirical field testing conducted over three days. The total daily energy demand was calculated to be 1,560 Wh/day. The designed system integrates a 400 Wp monocrystalline PV module, a 12 V 300 Ah lead-acid battery bank, a 45 A MPPT solar charge controller, and a 1000 W pure sine wave inverter. Simulation results showed a Performance Ratio (PR) of 66.71% and a Solar Fraction of 93.56%, with an estimated annual energy yield of 554.44 kWh. Field measurements demonstrated that the system was capable of stably supplying power to 13 LED lighting points for 12 hours, with the PV module producing a peak output power of 150 W under fluctuating solar irradiance conditions. The study concludes that the proposed PLTS system is technically feasible and provides a reliable alternative energy solution for remote aquaculture operations.

Keywords:
Photovoltaic System; off-grid; aquaculture ponds;performance; bori appakah

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1. Introduction

Electrical energy has become a fundamental requirement for supporting modern economic activities, including agricultural and aquaculture sectors. The increasing global demand for sustainable and environmentally friendly energy systems has accelerated the transition from fossil-based electricity generation toward renewable energy technologies. In Indonesia, the government has targeted a renewable energy contribution of 23% in the national energy mix by 2025 through the National Energy General Plan (RUEN). Among various renewable energy resources, solar energy has emerged as one of the most promising alternatives due to its abundant availability, environmental sustainability, and continuously decreasing installation costs.

Indonesia is geographically located in the equatorial region and receives relatively high solar irradiation throughout the year. In particular, South Sulawesi Province possesses significant solar energy potential, with average daily solar irradiation ranging from approximately 4.8 to 5.1 kWh/m²/day, making the region highly suitable for photovoltaic (PV)-based power generation systems. Consequently, Solar Power Plants (PLTS) have increasingly been considered an effective solution for rural electrification and isolated areas where conventional grid extension is technically difficult or economically infeasible. Previous studies have demonstrated that off-grid photovoltaic systems can provide reliable electrical energy for remote applications with relatively low operational costs and reduced environmental impact [1, 2].

Recent developments in photovoltaic technologies have also improved system reliability and operational efficiency under tropical environmental conditions. In [3] reported that environmental factors such as temperature and humidity significantly influence photovoltaic degradation and performance. Furthermore, in [4] emphasized the importance of optimal energy management strategies and component sizing to improve the operational reliability of standalone photovoltaic systems. In [5] further demonstrated that PVsyst simulation software can provide accurate performance predictions when validated using real operational data. In addition, optimization techniques and floating photovoltaic systems have been shown to improve overall system efficiency and operational flexibility [6]. Comprehensive reviews on renewable energy technologies also confirmed the growing role of photovoltaic systems in achieving sustainable energy transitions worldwide [7].

The implementation of renewable energy systems in aquaculture and fishery sectors has received considerable attention in recent years. In [8] reported that fishery–photovoltaic integration offers substantial potential for sustainable energy production and climate mitigation. Similarly, In [9] demonstrated the techno-economic feasibility of solar PV systems for shrimp pond aeration applications. In [10] proposed a hybrid solar–wind energy system capable of improving energy sustainability in aquaculture operations. In addition, IoT-integrated photovoltaic systems have increasingly been utilized to improve monitoring capability and operational efficiency in aquaculture environments [11, 12]. Renewable-energy-based aquaculture systems, including aquaponics and fish feed processing applications, have also shown promising results in supporting sustainable fish farming activities [13, 14]. Moreover, hybrid off-grid photovoltaic systems have demonstrated their capability to support recirculating aquaculture systems with improved energy reliability [15].

The aquaculture sector in Bori Appakah Village, Pangkep Regency, represents one of the areas experiencing limited access to reliable electrical infrastructure. The fishpond investigated in this study covers an area of approximately 4000 m² and requires continuous nighttime illumination to support aquaculture operations. Artificial lighting plays a dual role in the pond ecosystem. First, it functions as a phototactic stimulus that helps maintain fish and shrimp activity within safe cultivation zones. Second, the lighting system acts as passive security infrastructure to reduce the risk of theft and predator attacks during nighttime operations. Despite its importance, the pond location is situated approximately 1 km away from the nearest low-voltage utility grid operated by the national electricity company (PLN). Extending the conventional electrical network to the site would require substantial investment costs and may lead to significant voltage drop losses along the distribution line, thereby reducing overall system reliability and economic feasibility.

Although numerous studies have investigated photovoltaic applications for agriculture and aquaculture sectors, most previous works mainly focused on simulation-based analysis or specific subsystem applications such as aeration and water monitoring. Comprehensive studies involving the design, implementation, and real-field validation of off-grid photovoltaic systems for aquaculture pond lighting in remote coastal areas remain limited, particularly under tropical environmental conditions in Indonesia. Therefore, there is still a need for empirical studies evaluating the actual operational performance of standalone PV systems designed for fishpond electrification.

This study proposes the design and implementation of an off-grid solar photovoltaic system for aquaculture pond electrification in Bori Appakah, Pangkep Regency. The proposed system is designed to supply an electrical load demand of 1,560 Wh/day using photovoltaic modules, battery storage, solar charge controllers, and inverter units. System performance is evaluated through both PVsyst simulation and real-field operational measurements to assess the effectiveness and reliability of the proposed design.

The main contributions of this research are threefold. First, the study presents an optimal sizing approach for off-grid PV components suitable for remote aquaculture applications. Second, it provides a comparative analysis between simulation results and real operational performance under tropical environmental conditions. Third, the research evaluates the system feasibility based on key performance indicators, including Performance Ratio (PR) and Solar Fraction, to determine the capability of the system for continuous and sustainable operation. The results of this study are expected to contribute to the development of renewable-energy-based electrification systems for remote aquaculture sectors in Indonesia and other similar tropical regions.

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2. Method

A. Research Stages

This study was conducted using a quantitative experimental approach, consisting of literature review, electrical load energy auditing, manual system sizing calculations, software-based simulation, hardware assembly, and field testing.

Figure 1. Location map of the fish pond in Bori Appakah, located approximately 1 km from the PLN utility grid.

A. System Design (Sizing)

The proposed off-grid photovoltaic (PV) system was designed based on the daily electrical energy demand of the fish pond area. The main system specifications are summarized as follows:

- Daily Load Demand: 1,560 Wh/day
- PV Module Capacity: 400 Wp monocrystalline solar panel
- Battery Capacity: 300 Ah (3 × 100 Ah, 12 V batteries connected in parallel)
- Power Conditioning Unit: 45 A MPPT Solar Charge Controller and 1000 W Pure Sine Wave inverter

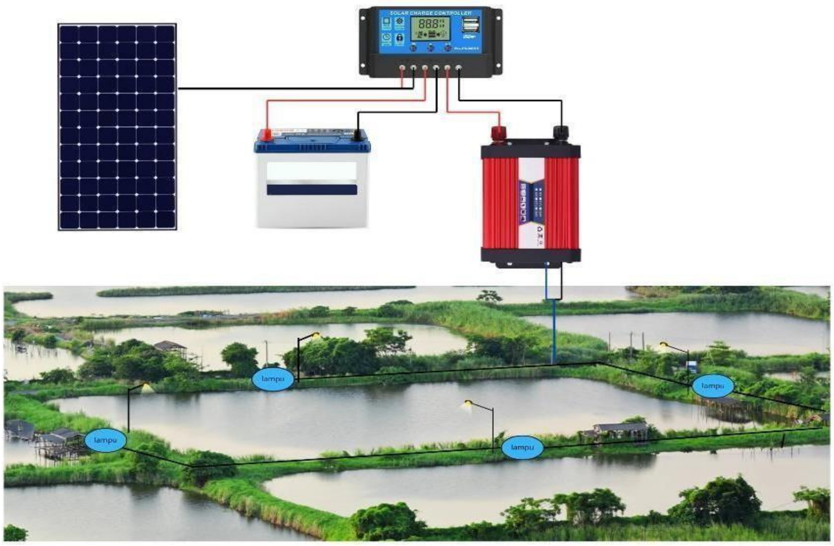


Figure 2. Wiring diagram of the proposed off-grid PV system.

B. Electrical Load Requirement

Table 1. Electrical Load Distribution of the Fish Pond

No	Load Type	Power (W)	Quantity	Operating Time (h/day)	Energy Consumption (Wh/day)
1	Fish Pond Lamps	10	11	12	1,320
2	Terrace Lamp	10	1	12	120
3	Indoor Lamp	10	1	12	120
	Total Daily Energy Demand				**1,560**

To account for system losses, component inefficiencies, and safety factors, the required energy production from the PV system was increased by 25%.
Given:

- Total daily energy demand = 1,560 Wh/day
- System loss/safety factor = 25%

The required PV energy production is calculated as:

- $E_{PV} = E_{total}(1 + 0.25) = 1560 \times 1.25 = 1950 \text{ Wh/day}$

Thus, the PV system must produce approximately 1,950 Wh/day.

1) PV Module Sizing

The number of PV modules was determined based on the required energy production and Peak Sun Hours (PSH).
Given:

- Required PV energy = 1,950 Wh/day
- PV module rating = 400 Wp
- PSH = 5.37 h/day

The daily energy generated by one PV module is:

$$E_{panel} = 0.4 \times 5.37 = 2.148 \text{ kWh/day}$$

The required number of PV modules is:

$$N = \frac{E_{PV}}{E_{panel}} = \frac{1.950}{2.148} = 0.91$$

Therefore, one 400 Wp PV module was selected, resulting in a total installed array capacity of 400 Wp.

2) Solar Charge Controller Sizing

The MPPT Solar Charge Controller rating was determined for a 12 V system with an additional 25% safety margin.
Given:

- Total PV array power = 400 W
- System voltage = 12 V

The base current is calculated as:

$$I_{base} = \frac{P_{PV}}{V_{sys}} = \frac{400}{12} = 33.33 \text{ A}$$

Considering a 25% safety margin:

$$I_{cc} = 33.33 \times 1.25 = 41.67 \text{ A}$$

Therefore, a 45 A MPPT Solar Charge Controller was selected.

3) Battery Capacity Sizing

Battery capacity was calculated by considering inverter efficiency and battery Depth of Discharge (DoD).
Given:

- Total load energy = 1,560 Wh
- Inverter efficiency = 90%

The required battery energy is:

$$E_{bat} = \frac{1560}{0.9} = 1733.33 \text{ Wh}$$

For a lead-acid battery with 50% DoD:

$$C = \frac{1733.33}{0.5} = 3466.67\ \text{Wh}$$

For a 12 V battery system:

$$Ah = \frac{3466.67}{12} = 288.89\ \text{Ah}$$

Thus, a 300 Ah battery bank at 12 V was selected.

4) Inverter Sizing

The inverter capacity was determined based on the total simultaneous AC load with a safety factor to accommodate surge current.

Given:

- Total AC load = 130 W
- Safety factor = 2–3

With a safety factor of 2:

$$P_{inv} = 130 \times 2 = 260\ \text{W}$$

With a safety factor of 3:

$$P_{inv} = 130 \times 3 = 390\ \text{W}$$

Therefore, a minimum 300 W pure sine wave inverter is required. However, a 500 W inverter is recommended to provide better surge handling capability and future load expansion flexibility.

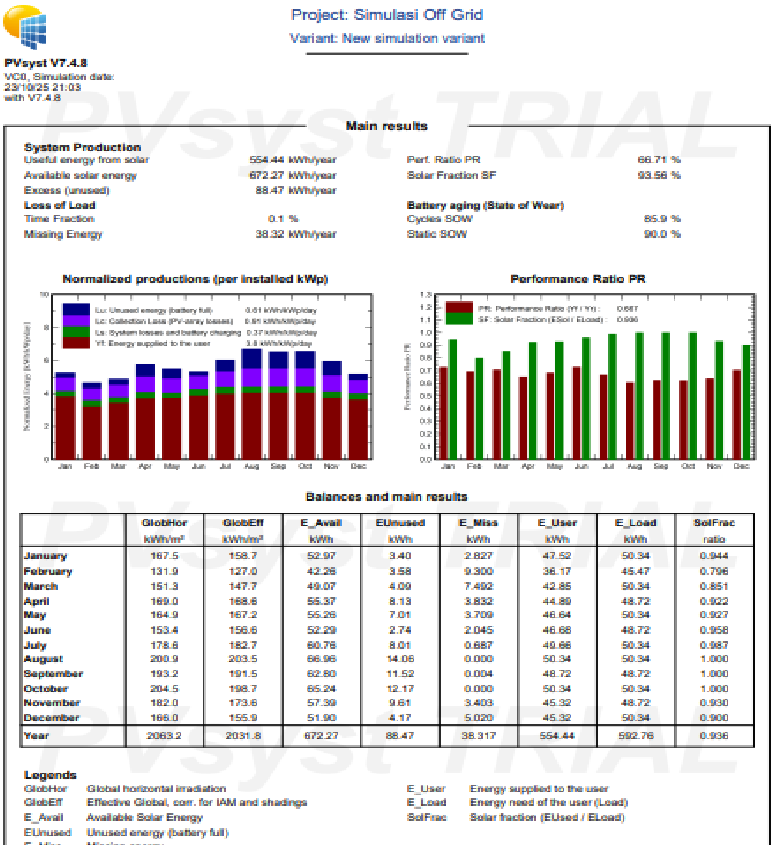
3. Result and Discussion

A. PVSyst Simulation Results

Based on Figure 3, the PVsyst simulation results indicate that the proposed off-grid photovoltaic system is capable of supplying electrical energy reliably for aquaculture pond operations. The system produced an annual useful energy output (E_User) of 554.44 kWh/year, while the total electrical load demand reached 592.76 kWh/year. The simulation also showed that the available solar energy generated by the PV array was 672.27 kWh/year, indicating sufficient solar resource potential to support the operational load requirements.

The average annual Performance Ratio (PR) obtained from the simulation was 66.71%, which reflects satisfactory system performance considering the influence of temperature losses, battery charging–discharging losses, inverter losses, and tropical environmental conditions. In addition, the Solar Fraction (SF) value reached 93.56%, indicating that approximately 93% of the total load demand could be supplied directly by the photovoltaic system. This result demonstrates that the proposed PLTS configuration is capable of operating with a high degree of energy independence and only requires minimal external energy support.

The simulation results also reveal that the unused energy reached 88.47 kWh/year, mainly occurring during periods of full battery charge conditions, whereas the missing energy was recorded at 38.32 kWh/year with a Loss of Load probability of only 0.1%. These findings indicate that the designed system possesses relatively good operational reliability and is suitable for continuous nighttime lighting applications in remote aquaculture ponds. Furthermore, monthly performance analysis shows that the system achieved optimal solar fraction values close to 1.0 during periods of high solar irradiation, particularly from July to October, confirming the strong correlation between solar availability and system energy performance..



Project: Simulasi Off Grid
Variant: New simulation variant

PVsyst V7.4.8
VC0, Simulation date:
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with V7.4.8

Main results

System Production

Useful energy from solar	554.44 kWh/year	Perf. Ratio PR	66.71 %
Available solar energy	672.27 kWh/year	Solar Fraction SF	93.56 %
Excess (unused)	88.47 kWh/year		
Loss of Load		**Battery aging (State of Wear)**	
Time Fraction	0.1 %	Cycles SOW	85.9 %
Missing Energy	38.32 kWh/year	Static SOW	90.0 %

Balances and main results

	GlobHor kWh/m²	GlobEff kWh/m²	E_Avail kWh	EUnused kWh	E_Miss kWh	E_User kWh	E_Load kWh	SolFrac ratio
January	167.5	158.7	52.97	3.40	2.827	47.52	50.34	0.944
February	131.9	127.0	42.26	3.58	9.300	36.17	45.47	0.796
March	151.3	147.7	49.07	4.09	7.492	42.85	50.34	0.851
April	169.0	168.6	55.37	8.13	3.832	44.89	48.72	0.922
May	164.9	167.2	55.26	7.01	3.709	46.64	50.34	0.927
June	153.4	156.6	52.29	2.74	2.045	46.68	48.72	0.958
July	178.6	182.7	60.76	8.01	0.687	49.66	50.34	0.987
August	200.9	203.5	66.96	14.06	0.000	50.34	50.34	1.000
September	193.2	191.5	62.80	11.52	0.004	48.72	48.72	1.000
October	204.5	198.7	65.24	12.17	0.000	50.34	50.34	1.000
November	182.0	173.6	57.39	9.61	3.403	45.32	48.72	0.930
December	166.0	155.9	51.90	4.17	5.020	45.32	50.34	0.900
Year	2063.2	2031.8	672.27	88.47	38.317	554.44	592.76	0.936

Legends

GlobHor	Global horizontal irradiation	E_User	Energy supplied to the user
GlobEff	Effective Global, corr. for IAM and shadings	E_Load	Energy need of the user (Load)
E_Avail	Available Solar Energy	SolFrac	Solar fraction (EUsed / ELoad)
EUnused	Unused energy (battery full)		

Gambar 3. Simulasi *Off-Grid*

B. Implementation Results

1) Solar PV Testing

Based on Figure 4, the testing results show that the current and output power of the solar panel increased gradually from 07:00 to approximately 10:00 as the intensity of solar radiation increased. During the period between 10:00 and 11:30, the current and power values reached near-maximum conditions, indicating that the photovoltaic modules operated under optimal irradiation conditions. However, several minor fluctuations were observed in the graph due to changes in weather conditions, such as passing clouds and variations in ambient temperature during the testing process.

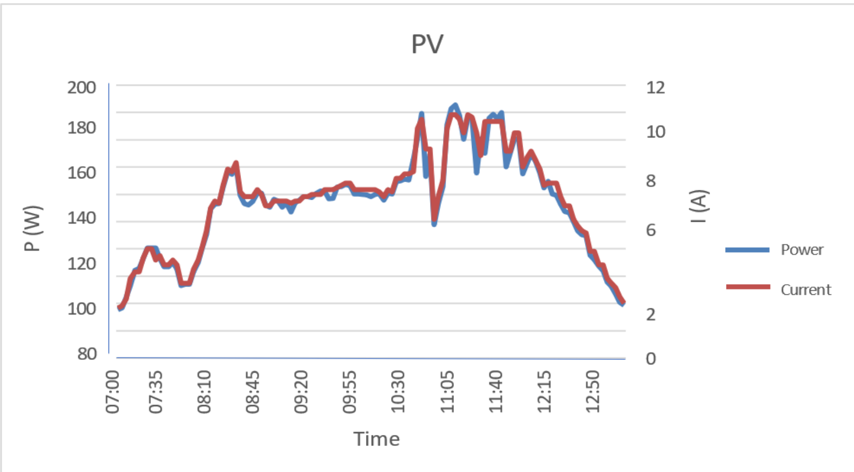

Figure 4. Graph of the relationship between current (A) and power (W) in solar PV

After 11:40 until 12:50, the PV current and output power gradually decreased. This condition was mainly caused by the increase in panel surface temperature, which reduced the efficiency of electrical energy conversion. Overall, the testing results indicate that the performance of the PV modules was strongly influenced by solar irradiation intensity and surrounding environmental conditions. Therefore, the designed photovoltaic system was able to generate power optimally under clear weather conditions while maintaining stable operating characteristics throughout the field testing process.

2) Battery Testing

Based on Figure 5, the graph illustrating the relationship between current and power in the battery system shows relatively stable characteristics throughout the testing period. During the morning period from 07:00 to 09:00, the current and power values remained at moderate levels with very small fluctuations, indicating that the initial battery charging process operated normally. This condition demonstrates that the energy generated by the solar panels was successfully transferred to the energy storage system.

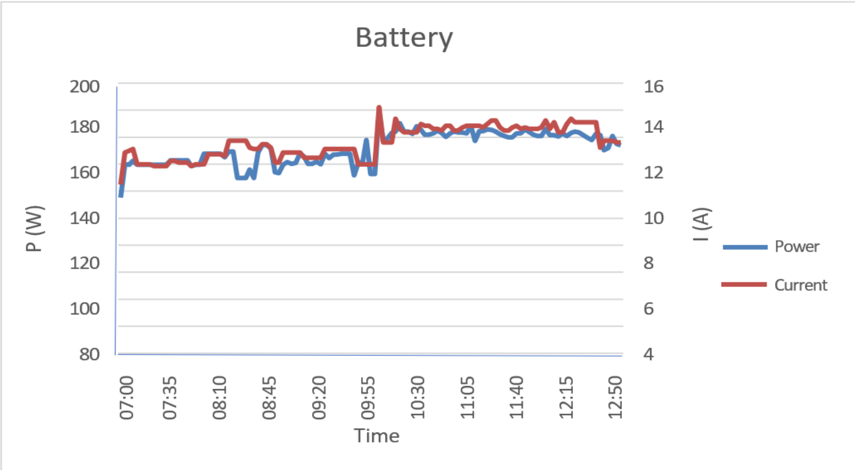

Figure 5. Graph of the relationship between current (W) and power (W) in a battery

Between 09:00 and 11:00, a slight increase in current and power was observed while the system remained stable. This indicates that the battery continuously received energy from the photovoltaic modules as solar irradiation increased. Furthermore, from 11:00 to 12:50, the current and power values returned to stable conditions, indicating that the battery entered a near fully charged state. Overall, the testing results confirm that the battery system operated stably and that the charging system effectively maintained controlled current and power during operation.

3) Inverter Testing

Based on Figure 6, the inverter testing results indicate that the inverter output current and power remained relatively stable throughout the observation period. At the beginning of the testing period, from 07:00 to 09:00, the current and power values were relatively constant without significant changes. This condition indicates that the inverter operated properly in supplying stable electrical power to the load.

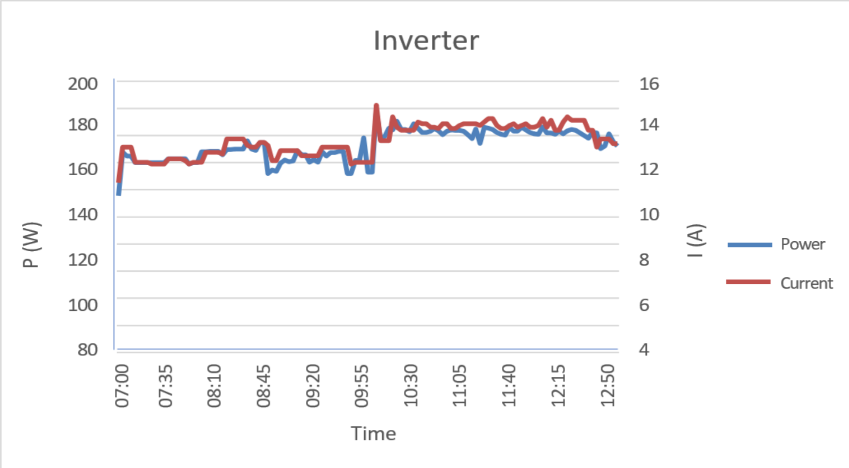

Figure 6. Graph of the relationship between current (A) and power (Watts) on the inverter

At approximately 09:30, a slight increase in current and output power was observed. This condition was likely caused by temporary load changes or the inverter response to increased energy supply from the battery and photovoltaic system. After this period, the current and power values returned to stable conditions until 12:50, indicating that the inverter had good output regulation capability. Overall, the testing results demonstrate that the inverter was capable of converting DC energy into AC power steadily without significant fluctuations, allowing the system to operate reliably during the field testing process.

4) Load Testing

Based on Figure 7, the graph illustrating the relationship between power and current on the load side shows that the system power consumption ranged between 110 W and 140 W during the testing period. The relatively stable power consumption indicates the presence of a constant base load throughout system operation. In addition, the load current remained stable at approximately 0.6 A from morning until afternoon, indicating that the inverter was capable of continuously supplying the required electrical demand.

However, between approximately 14:35 and 16:20, repeated current fluctuations between 0.6 A and 0.7 A were observed. This condition indicates the presence of additional cyclic loads operating periodically, resulting in temporary fluctuations in current demand. Despite these minor fluctuations during the afternoon period, the system was still able to maintain stable power delivery without significant operational disturbances. Overall, the results demonstrate that the designed off-grid photovoltaic system possesses good capability in supplying electrical energy to the load continuously and reliably during field testing.

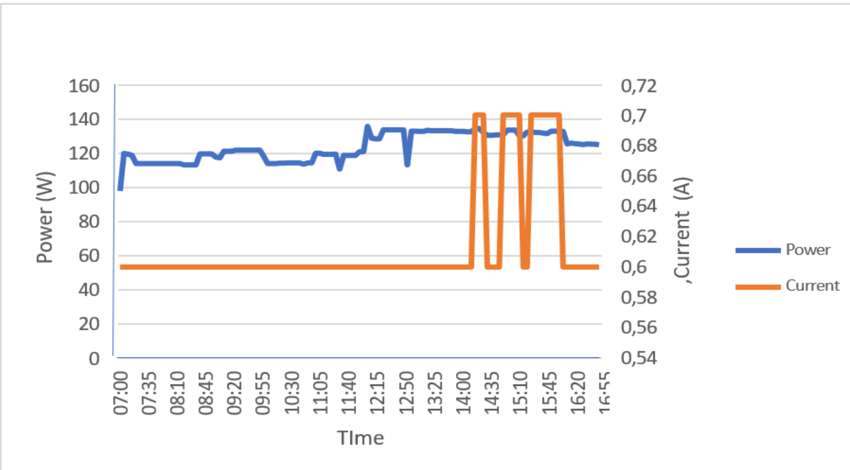

Figure 7. Graph of the relationship between current (A) and power (Watts) under load

4. Conclusion

1) The proposed off-grid photovoltaic system, consisting of a 400 Wp solar panel, 300 Ah 12 V battery, and 45 A MPPT solar charge controller, was successfully designed to supply an electrical load demand of 1,560 Wh/day for aquaculture pond lighting applications.
2) The PVsyst simulation results demonstrated that the system achieved a Performance Ratio (PR) of 66.71% and a Solar Fraction (SF) of 93.56%, indicating satisfactory operational performance and a high level of energy independence under tropical environmental conditions.
3) Field testing results confirmed that the designed photovoltaic system was capable of operating reliably and continuously for approximately 12 hours during nighttime operation. The system also exhibited stable performance in the photovoltaic modules, battery charging process, inverter output, and load supply throughout the testing period.
4) Overall, the proposed PLTS off-grid system is technically feasible and suitable for implementation in remote aquaculture areas lacking access to conventional electrical infrastructure. The study demonstrates the potential of solar energy utilization as a sustainable and environmentally friendly solution for supporting energy needs in coastal aquaculture sectors.

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