EMITOR: Jurnal Teknik Elektro

Design and Performance Evaluation of an Off-Grid Solar Powered Automatic Aquarium Water Filling System 100 Wp

Ardhe Mufti Ardi*, Sunardi
Program Studi Teknik Elektro, Fakultas Teknik – Universitas Pamulang
Tangerang Selatan, Indonesia
*ardheardi@gmail.com

Abstract – *The increasing use of aquariums in household environments requires a reliable and automated water filling system to maintain stable water volume. In general, aquarium water filling systems still rely on electric pumps powered by the public electricity grid (PLN), which increases electricity consumption and may cause operational disruptions during power outages. This study aims to design and experimentally evaluate the performance of an automatic aquarium water filling system based on a 100 Wp off-grid photovoltaic (PV) power system. The proposed system consists of a 100 Wp solar panel, a pulse-width modulation (PWM) solar charge controller, a 12 V 20 Ah VRLA battery, a DC–AC inverter, a single-phase water pump, and a float switch–based water level sensor. The system design was carried out based on load analysis and component requirement calculations, followed by experimental testing under real operating conditions. Performance evaluation included measurements of photovoltaic output characteristics, battery charging behavior, inverter output stability, and water pump performance during the aquarium filling process. The experimental results show that the photovoltaic system produced an average operating voltage of 13.72 V under solar irradiance conditions of up to approximately 1,000 W/m^2. The battery charging current ranged from 3.3 A to 6.3 A, with an average value of 5.9 A, and the battery voltage increased from 6.4 V to 12.6 V during the charging process. The inverter was able to maintain a relatively stable AC output voltage in the range of 232–234 V and supplied an average power of 36.9 W to the water pump during battery-powered operation. During aquarium filling tests, the water pump operated at a voltage range of 232–235 V with a current of 0.8–0.9 A and an electrical power range of 50.32–56.37 W. The system successfully filled a 90-liter aquarium with a filling time ranging from 12.85 to 18.01 minutes and a corresponding water flow rate of 5.00–6.71 L/min. These results demonstrate that a compact 100 Wp fully off-grid photovoltaic system integrated with battery energy storage, inverter-based AC operation, and float switch–based automatic control is capable of reliably supporting an automatic aquarium water filling process. This study provides experimental evidence that small-scale photovoltaic systems can serve as a practical and sustainable alternative energy source for household aquarium automation applications.*

Keywords – *Aquarium; Automatic water filling; Off-grid photovoltaic; Water pump; VRLA battery.*

I. Introduction

THE use of aquariums in household environments and small-scale commercial facilities continues to increase, creating a demand for supporting systems that are reliable and easy to operate. One important aspect of aquarium maintenance is controlled water filling to maintain stable water volume and ensure fish survival. Manual water filling processes are prone to volume inaccuracies, require additional time and effort, and are difficult to perform consistently [1].

Aquarium water filling systems generally still rely on electric pumps directly supplied by the public electricity grid (PLN). This dependence not only increases household electricity consumption but also introduces potential operational disruptions during power outages or voltage fluctuations. These conditions highlight the need for an automatic, independent aquarium water filling system with improved energy resilience [2].

Indonesia has significant solar energy potential due to its tropical location, which provides relatively high solar irradiance throughout the year. Small-scale photovoltaic (PV) power systems represent a relevant solution, as they can operate in off-grid configurations, produce no emissions during operation, and are relatively easy to implement for household applications. The integration of PV systems with automation technologies offers an opportunity to enhance energy independence in small-scale devices, including automatic aquarium water filling systems [3].

The manuscript was received on January 20, 2026, revised on January 23, 2026, and published online on March 27, 2026. Emitor is a Journal of Electrical Engineering at Universitas Muhammadiyah Surakarta with ISSN (Print) 1411 – 8890 and ISSN (Online) 2541 – 4518, holding Sinta 3 accreditation. It is accessible at https://journals2.ums.ac.id/index.php/emitor/index.

Several previous studies have explored the application of photovoltaic (PV) systems as energy sources for water pumping applications, primarily targeting irrigation systems, groundwater extraction, and general-purpose water distribution. Arifin *et al.* [2] designed a solar-powered water pump system to reduce household electricity consumption, while Hutajulu *et al.* [4] implemented an on-grid PV system for supplying electrical loads in public facilities. Suratno and Cahyono [1] investigated a PV-based power supply for a submersible water pump, focusing on system feasibility and electrical performance. Similarly, Teknik and Listrik [5] analyzed the design and performance of a solar-powered water pumping system for general applications. The studies confirm the technical viability of PV-driven pumping systems, but with notable limitations in scale, configuration, and operational complexity. Gunasekaran and Chakraborty (2023) recommend standalone systems for areas with a maximum 50 m dynamic head and at least 2,000 m from grid power [6]. Chilundo *et al.* (2018) found that most configurations are direct-coupled systems without battery storage, primarily used for small-scale irrigation and domestic use [7]. Sharma *et al.* (2020) identified persistent challenges including diminishing water levels, low power availability during early and late hours, and high installation costs [8]. Overall, the research predominantly focuses on small- to medium-capacity installations, with reported system efficiencies typically not exceeding 10%, indicating significant room for technological improvement in PV pumping systems [6–8].

Existing research partially addresses low-capacity, off-grid PV systems for aquarium water level control, but does not fully meet the specific requirements outlined in the research question. The most promising approach is proposed by Chiagunye *et al.* (2025), who developed an automated aquarium monitoring system powered by a 30 W solar panel with automated water replacement capabilities [9]. Similarly, Kok *et al.* (2024) proposed an IoT-based system with water level monitoring, although it was not specifically designed for off-grid applications [10]. London (2025) demonstrated a solar-powered water pumping system using an ultrasonic sensor to measure water levels, which comes close to the desired mechanism for automatic water level control [11]. However, none of the studies fully satisfy the exact specifications of a low-capacity, fully off-grid PV system specifically designed for household aquarium water level maintenance. This confirms the research question's assertion of an existing technological gap in the development of compact, autonomous, and energy-independent aquarium water management systems [9–11]. Most reported systems are manually operated, lack closed-loop water level sensing, or are designed for continuous pumping rather than event-driven filling triggered by real-time demand. In addition, experimental evaluations in prior studies largely focus on electrical output characteristics and overall energy feasibility, with limited attention to practical system behavior, such as inverter stability under intermittent loads, battery charging dynamics during short-duty cycles, and hydraulic performance during controlled filling operations. These limitations indicate a clear research gap in the development and experimental validation of compact, low-power, autonomous PV-based water filling systems tailored for small-scale aquarium automation.

The sources confirm the research question's premise: there is indeed a lack of fully validated, low-power, off-grid solutions specifically designed for aquarium water filling. While promising technologies exist, such as the automated solar-powered system using an ultrasonic water level sensor proposed by Sarwar and Iqbal (2022) [12] and the IoT-based water changing system developed by Kok *et al.* (2024) [10], these systems are not comprehensively designed for aquarium-specific water filling applications. In addition, most current photovoltaic water pumping systems primarily focus on agricultural irrigation or rural water extraction, as demonstrated in the low-power PV pumping system proposed by Fey *et al.* (2020) [13]. Therefore, despite the existence of several technically mature photovoltaic water pumping and automation technologies, a clear gap remains in the development of a compact, low-capacity, and fully off-grid photovoltaic system specifically tailored for household aquarium water level maintenance.

Based on these considerations, this study focuses on the design and performance evaluation of an automatic aquarium water filling system based on a 100 Wp off-grid photovoltaic (PV) power system. The system is designed to operate a single-phase water pump supported by energy storage and automatic control using a water level sensor. The research describes an innovative automated aquarium water filling system powered by a 100 Wp off-grid photovoltaic (PV) system with integrated water level sensor control. The system's design leverages solar power and automated sensing technologies to manage water levels autonomously. Similar studies demonstrate the feasibility of such systems, with Chiagunye *et al.* (2025) [9] presenting an automated aquarium monitoring system powered by a 30 W solar panel with precise water quality management. Febriani *et al.* (2024) [14] further validated the effectiveness of off-grid solar systems by demonstrating an average daily energy generation of 503.8 Wh, which was sufficient to power water circulation pumps in aquaponics applications. In addition, Sarwar and Iqbal (2022) [12] provided empirical evidence of water level sensor automation using microcontroller-based control, in which pumps are automatically switched on and off based on real-time water level conditions. These studies collectively confirm the technical feasibility of integrating photovoltaic energy systems with automated water level sensing technologies, thereby supporting the conceptual foundation of the proposed off-grid photovoltaic-based automatic aquarium water filling system.

Performance evaluation is carried out through experimental testing of electrical parameters, battery charging characteristics, inverter output stability, and water pump performance during the aquarium filling process. The results of this study are expected to provide an applied contribution to the utilization of small-scale PV systems as alternative energy sources for reliable and sustainable aquarium automation systems. Solar photovoltaic systems demonstrate promising performance for aquarium and aquaponics automation, exhibiting robust electrical and operational characteristics. Multiple studies provide concrete evidence of system reliability. Febriani *et al.* (2024) [14] reported an off-grid solar PV system generating an average daily energy of 503.8 Wh, which was sufficient to power water circulation for up to 20 hours, with a measured solar panel efficiency of 4.97% and a pump efficiency of 79.91%. Masthura and Armansyah (2023) [15] documented detailed electrical performance parameters, recording output voltage ranges from 17.68 to 18.90 V and current ranges from 4.98 to 6.22 A under clear weather conditions. Lubis *et al.* (2024) [16] further validated these findings by demonstrating solar panels producing an average voltage of 40.83 V and a current of 3.28 A, with an overall system efficiency of 40.65%. Collectively, these studies support the potential of small-scale photovoltaic systems as reliable alternative energy sources for aquarium and aquaponics automation.

In contrast to most existing PV-based pumping studies that emphasize irrigation and large-capacity water supply systems, this work specifically addresses the design and experimental evaluation of a low-power, fully off-grid PV system integrated with automatic water level control for aquarium applications. The novelty of this study lies in the practical integration of a 100 Wp photovoltaic module, PWM charge controller, VRLA battery storage, inverter, and float switch sensor into a compact and autonomous aquarium water filling system, followed by a comprehensive performance assessment under real operating conditions. The main contributions of this paper include: (i) the development of a complete off-grid PV-powered automatic aquarium filling prototype; (ii) experimental characterization of PV output, battery charging behavior, inverter stability, and pump performance; and (iii) validation of system feasibility for small-scale household automation. These contributions provide applied insights into the utilization of low-capacity photovoltaic systems for reliable, sustainable, and autonomous aquarium water management.

II. Research Methods

An automatic aquarium water filling system is designed to maintain stable water volume continuously without manual intervention. The use of automation in aquarium systems aims to improve operational reliability, reduce filling errors, and maintain stable environmental conditions for fish. Generally, such systems utilize a water pump as the main actuator controlled by a water level sensor, such as a float switch or other level sensors. When the water level falls below a predefined threshold, the system automatically activates the pump and stops it once the desired water level is reached [4, 17].

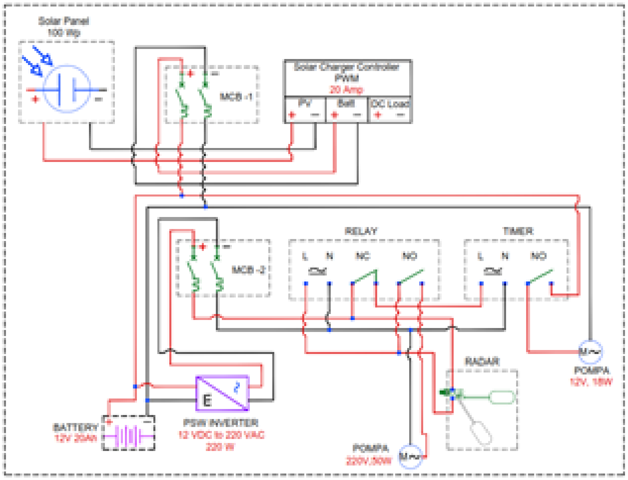

Figure 1: Conceptual diagram of an automatic aquarium water filling system based on an off-grid photovoltaic power supply.

In conventional implementations, aquarium water pumps still depend on electricity supplied by the public power grid (PLN). This dependence introduces several limitations, particularly during power outages or voltage fluctuations that can disrupt the water filling process. Therefore, an alternative energy source is required to support the independent and sustainable operation of automatic aquarium water filling systems [18].

i. Small-Scale Photovoltaic (PV) Power System

A photovoltaic (PV) power system converts solar radiation energy into electrical energy through the photovoltaic effect. Small-scale PV systems are widely applied in household applications and standalone (off-grid) systems due to their advantages, including ease of installation, zero emissions during operation, and the ability to supply electrical energy independently without reliance on the main power grid [5, 19].

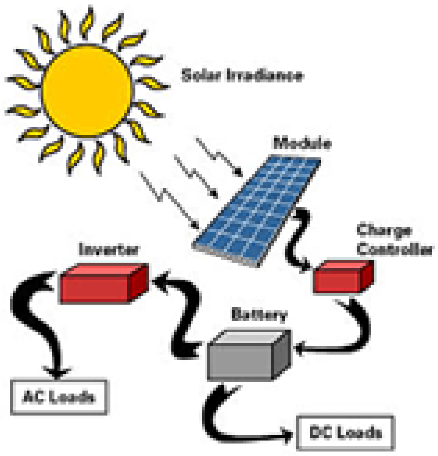

Figure 2: Process of utilizing solar energy through a photovoltaic power generation system.

Several previous studies have demonstrated that photovoltaic (PV) systems can be utilized as energy sources for operating water pumps, particularly for applications such as irrigation, water wells, and agricultural water supply. However, most of these studies focus on systems with relatively large power capacities and are intended for large-scale water demand. The application of small-capacity PV systems for specific purposes, such as automatic aquarium water filling systems, remains relatively limited and has not been extensively evaluated through experimental studies [1, 5].

ii. Solar Charge Controller (SCC)

A solar charge controller (SCC) functions to regulate the energy charging process from the solar panel to the battery to ensure safe and optimal operation. The SCC prevents overcharging and over-discharging conditions that can shorten battery lifespan. In general, SCCs are classified into two main types, namely pulse width modulation (PWM) and maximum power point tracking (MPPT) [1, 19].

MPPT-type solar charge controllers offer higher efficiency because they are able to track and operate at the maximum power point of the solar panel, particularly under low irradiance conditions. However, PWM-type SCCs are still widely used in small-scale PV systems due to their simpler structure, lower cost, and sufficient performance for systems with limited power capacity and relatively high irradiance conditions. The selection of an appropriate SCC type in a PV system should be adjusted to the load characteristics, system capacity, and application objectives [3].

iii. Battery Energy Storage System

Batteries serve as electrical energy storage media in off-grid photovoltaic (PV) systems. Since the energy generated by solar panels is not always continuously available, batteries are required to store energy and supply power when solar irradiance decreases or is unavailable. In small-scale PV systems, valve-regulated lead-acid (VRLA) batteries are still widely used due to their sealed construction, relatively easy maintenance, and lower cost compared to other battery technologies [1, 19].

Figure 3: Battery energy storage system in an off-grid photovoltaic installation.

Battery capacity is determined based on the load energy requirements and the system operating duration. Proper battery capacity design is essential to ensure a stable power supply and to maintain battery lifespan over long-term operation [3, 20].

iv. Water Pump as the System Load

The water pump is the main component in an automatic aquarium water filling system, functioning to transfer water from the source to the aquarium. In this system, a single-phase water pump is used due to its simple construction and suitability for small-scale applications. The performance of the water pump is influenced by several parameters, including operating voltage, electric current, power consumption, and flow characteristics such as flow rate and filling time [20, 21].

In photovoltaic-based systems, the water pump must be matched with the system's power supply capability to ensure stable operation. Therefore, analysis of the water pump characteristics is an important part of the design of a solar-powered automatic aquarium water filling system [4].

Based on the literature review presented above, it can be concluded that the utilization of photovoltaic (PV) systems as energy sources for water pumps has been widely applied in various applications, particularly for irrigation, groundwater extraction, and agricultural water supply [1, 2, 4, 5]. However, most existing studies still focus on medium- to large-capacity systems and do not specifically address small-scale PV-based automatic aquarium water filling systems. In addition, comprehensive experimental studies evaluating the performance of automatic aquarium water filling systems, including electrical parameters, battery charging behavior, inverter stability, and water pump hydraulic performance, remain relatively limited.

Therefore, this study is directed at addressing this research gap by designing and evaluating the performance of a 100 Wp off-grid photovoltaic (PV)-based automatic aquarium water filling system. The results are expected to provide an applied contribution to the utilization of solar energy for small-scale aquarium automation systems and to support the development of compact, reliable, and energy-independent household water management solutions.

This study employs a design-and-implementation approach combined with experimental testing to design, realize, and evaluate the performance of an automatic aquarium water filling system based on an off-grid photovoltaic (PV) power system. The design-and-implementation method was selected because the study focuses on integrating multiple electrical and mechanical components into a single system capable of operating independently.

An experimental approach is employed to directly evaluate system performance under real operating conditions. Through experimental testing, electrical parameters and water pump performance can be observed, measured, and analyzed, allowing the research results to objectively represent system performance and be reproducible.

Figure 4: Single-phase water pump used as the main load in the automatic aquarium water filling system.

v. Research Stages

The research stages were carried out systematically to ensure consistency between system design, implementation, and performance evaluation. In general, the research stages include: (i) literature review; (ii) load requirement analysis; (iii) system design and assembly; (iv) system testing; and (v) data analysis and performance evaluation.

vi. System Configuration and Operating Principle

The automatic aquarium water filling system is designed as an off-grid photovoltaic (PV) system, in which electrical energy is generated by a solar panel and stored in a battery before being used to operate the water pump. The solar panel functions to convert solar radiation energy into direct current (DC) electrical energy, which is then regulated by a solar charge controller (SCC) during the battery charging process.

The electrical energy stored in the battery is subsequently converted by the inverter from direct current (DC) to alternating current (AC) at 220 V to supply the single-phase water pump. Pump operation is automatically controlled using a float switch-based water level sensor. When the aquarium water level falls below a predefined threshold, the sensor activates the pump, and the pump is automatically turned off once the water level reaches the maximum limit.

vii. Water Pump

A single-phase water pump is used as the main load of the automatic aquarium water filling system. Based on the manufacturer's specifications, the water pump has a nominal power rating of 50 W and an operating voltage of 220 V AC. The technical specifications of the water pump used in this study are presented in Table 1. The daily energy requirement of the water pump is calculated to determine the minimum capacity of the photovoltaic (PV) system using (1).

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

where E_d represents the daily energy requirement (Wh), P is the pump power (W), and t is the daily operating time of the pump (hours). Assuming a pump operating duration of 3 hours per day, the daily energy requirement obtained from (1) is:

$$E_d = 50 \times 3 = 150 \text{ Wh/day} \tag{2}$$

The value in (2) is subsequently used as the basis for solar panel sizing in (3), SCC sizing in (5), battery sizing in (7), and inverter sizing in (9).

Table 1: Specifications of the water pump.

Parameter	Specification
Pump type	Kandila ORCA 106
Rated voltage	220 V
Frequency	50–60 Hz
Phase	Single phase
Rated power	50 W
Maximum flow rate	4000 L/hour

viii. Solar Panel Planning and Selection

The solar panel capacity is determined based on the system's daily energy requirements and the effective duration of solar irradiance. The solar panel serves as the primary energy source, converting solar radiation into direct current (DC) electrical energy. The minimum required solar panel power is calculated using (3).

$$P_{PV} = \frac{E_d}{H_s} \tag{3}$$

where P_{PV} represents the minimum required solar panel power (W) and H_s is the effective solar irradiance duration (hours). Assuming an effective solar irradiance duration of 5 hours per day, the minimum required solar panel power obtained from (3) is:

$$P_{PV} = \frac{150}{5} = 30 \text{ W} \tag{4}$$

The value in (4) represents the theoretical minimum requirement. To account for variations in solar irradiance and system losses, a 100 Wp solar panel is selected to provide an adequate safety margin for system operation. The technical specifications of the solar panel used in this study are presented in Table 2.

Table 2: Specifications of the solar panel.

Parameter	Specification
Model number	SM100-18P
Rated maximum power (P_m)	100 W
Cell efficiency	16.93%
Tolerance	±3%
Voltage at P_{max} (V_{mp})	17.8 V
Open-circuit voltage (V_{oc})	21.8 V
Current at P_{max} (I_{mp})	5.62 A
Short-circuit current (I_{sc})	6.05 A
Maximum system voltage	1000 VDC
Operating temperature	−4°C to +85°C
Cell technology	Monocrystalline
Connector	MC4 plug type
Dimension	920 × 680 × 30 mm

ix. Solar Charge Controller (SCC) Capacity Calculation

The solar charge controller (SCC) functions to regulate the energy charging process from the solar panel to the battery to ensure safe and optimal operation. The SCC capacity is determined based on the maximum current generated by the solar panel. The minimum required SCC current is calculated using (5).

$$I_{SCC} = \frac{P_{PV}}{V_{sys}} \times SF \tag{5}$$

where I_{SCC} is the minimum required SCC current (A), P_{PV} is the solar panel power (W), V_{sys} is the system voltage (V), and SF is the safety factor with a value of 1.25. Using a solar panel power of 100 W and a panel operating voltage of 17.8 V, the required SCC current obtained from (5) is:

$$I_{SCC} = \frac{100}{17.8} \times 1.25 = 7.02 \text{ A} \tag{6}$$

Based on the result in (6), a PWM-type solar charge controller with a current rating of 10 A is selected to meet the system requirements. The specifications of the SCC used in the system are presented in Table 3.

Table 3: Specifications of the solar charge controller.

Parameter	Specification
Controller type	PWM
Controller model	W88-B
Rated system voltage	12 V / 24 V
Rated charging current	10 A
Maximum PV input power (12 V)	–

x. Battery Capacity Calculation

The battery is used as an electrical energy storage medium in the off-grid photovoltaic (PV) system. The battery capacity is designed to ensure that the system can continue operating even when solar energy supply is unavailable for a certain period of time. The battery capacity is calculated using (7).

$$C_{bat} = \frac{E_d}{V_{bat} \times DoD} \tag{7}$$

where C_{bat} is the battery capacity (Ah), E_d is the daily energy requirement (Wh), V_{bat} is the battery voltage (V), and DoD is the depth of discharge, assumed to be 80%. Based on the calculation from (7), the minimum required battery capacity is obtained as:

$$C_{bat} = \frac{150}{12 \times 0.8} = 15.6 \text{ Ah} \tag{8}$$

To enhance system reliability and provide energy backup, a 20 Ah VRLA battery is selected. The specifications of the battery used in this study are presented in Table 4.

Table 4: Specifications of the battery.

Parameter	Specification
Model	6-DZF-20
Nominal voltage	12 V
Capacity	20 Ah
Battery type	VRLA / Gel type
Weight	6.4 kg

xi. Inverter Capacity Calculation

The inverter functions to convert DC voltage from the battery into 220 V AC voltage required by the water pump. The determination of inverter capacity considers the load power, inverter efficiency, and a safety factor to accommodate the initial current surge of the pump. The inverter capacity is calculated using (9).

$$P_{inv} = \frac{P_{load} \times SF}{\eta} \tag{9}$$

where P_{inv} is the minimum required inverter power (W), P_{load} is the load power (W), SF is the safety factor with a value of 1.25, and η is the inverter efficiency, assumed to be 80%. Based on the calculation from (9), the minimum required inverter power is obtained as:

$$P_{inv} = \frac{50 \times 1.25}{0.8} = 78.12 \text{ W} \tag{10}$$

Based on the result in (10), the inverter used has a nominal power rating of 220 W with a surge power capability of up to 1000 W to accommodate the initial current of the water pump. The specifications of the inverter used in this study are presented in Table 5.

Table 5: Specifications of the inverter.

Parameter	Specification
Input voltage	DC 12 V
Output voltage	AC 220 V
Maximum output power	1000 W
Continuous power	500 W
Frequency	50 Hz
Dimension	185 × 95 × 55 mm
Inverter efficiency	95%
Weight	1.35 kg

III. Results and Discussion

The design results indicate that the 100 Wp off-grid photovoltaic (PV)-based automatic aquarium water filling system was successfully realized in accordance with the planned configuration. All main components, including the solar panel, solar charge controller, battery, inverter, water pump, and water level sensor, were successfully integrated into a single system that operates automatically. The physical implementation of the system is presented in Fig. 5, which illustrates the PV control panel and the overall aquarium water filling system.

(a) (b)

Figure 5: Implementation of the off-grid solar-powered automatic aquarium water filling system (a) PV control panel consisting of SCC, battery, and inverter (b) Integrated automatic aquarium water filling system

The system implementation in Fig. 5 demonstrates that the integration of the photovoltaic (PV) system with the automatic control system is capable of providing a stable power supply to support the aquarium water filling process. The water level sensor operates as designed, in which the water pump is activated when the water level falls below the minimum threshold and automatically stops once the water level reaches the maximum limit, as observed during the operation shown in Fig. 5.

i. No-Load Photovoltaic System Test Results

No-load testing of the photovoltaic (PV) system was conducted to evaluate the output characteristics of the solar panel and the battery charging process without the influence of the water pump load. The parameters observed in this test included the solar panel output current and voltage, battery charging current and voltage, solar irradiance intensity, and panel temperature. The test was carried out under natural environmental conditions with a fixed panel tilt angle of 15°.

The average results of the no-load photovoltaic (PV) system testing over five days of observation are presented in Table 6. Based on Table 6, solar irradiance intensity varied within the range of 569.48–1009.14 W/m^2, which influenced the magnitude of the solar panel output current. The panel current tended to increase with increasing irradiance intensity, with a maximum current of 2.95 A recorded at 11:00. The panel output voltage ranged from 12.78 V to 15.86 V, which remains within the operating characteristics of a 12 V PV system.

Table 6: Average results of no-load PLTS system testing over five days.

Time	Solar Panel Output		Battery Charging		Solar Irradiance	Panel Temp.
	Current (A)	Voltage (V)	Current (A)	Voltage (V)	(W/m^2)	(°C)
09:00	1.99	13.26	1.66	12.50	833.88	32.9
09:30	2.19	13.90	1.84	12.87	903.48	37.26
10:00	2.39	15.86	2.70	12.89	1009.14	39.24
10:30	2.36	13.71	2.41	12.79	710.36	41.62
11:00	2.95	14.00	3.10	12.91	886.22	43.10
11:30	2.75	13.62	2.84	12.84	569.48	43.40
12:00	2.15	13.47	2.42	12.61	796.46	41.58
12:30	2.12	13.45	2.52	12.62	877.82	43.60
13:00	2.26	13.25	2.60	12.59	936.86	42.70
13:30	1.80	12.86	2.16	12.36	844.56	45.00
14:00	1.55	12.78	1.52	12.18	685.64	41.70

In addition, the battery charging voltage exhibited relatively stable values in the range of 12.18–12.91 V as reported in Table 6. This indicates that the solar charge controller is able to regulate the battery charging process effectively despite fluctuations in solar irradiance and panel temperature. An increase in panel temperature up to 45°C contributed to a reduction in panel voltage at several observation periods, which is a common characteristic of photovoltaic modules, as can also be inferred from the voltage trend in Table 6.

The relationship between solar irradiance intensity and the output current and voltage of the solar panel is shown in Fig. 6. Based on Fig. 6, the solar panel output current increases proportionally with solar irradiance, while the panel voltage remains relatively stable with minor fluctuations.

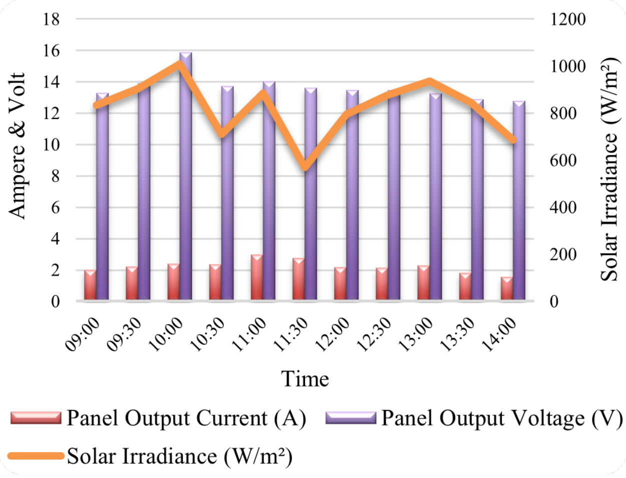

Figure 6: Relationship between solar irradiance and solar panel output current and voltage under no-load conditions.

ii. Battery Charging Characteristics

Battery charging characteristics were observed to evaluate the performance of the photovoltaic (PV) system in delivering energy from the solar charge controller (SCC) to the battery. The test was conducted under no-load conditions of the water pump, so that the measured parameters directly represent the battery charging process without the influence of external loads. The observed parameters included the SCC output voltage and current to the battery, charging power, and battery voltage during the testing period.

The results of the battery charging characteristic test are presented in Table 7. Based on Table 7, the battery charging current ranged from 3.3 A to 6.3 A, with an average value of 5.9 A. The SCC output voltage delivered to the battery increased over the testing period, with an average value of 11.62 V. The battery charging power recorded an average value of 59.15 W, indicating that the energy transfer process from the SCC to the battery occurred in a stable manner.

Table 7: Battery charging test results.

Time	Charging from SCC to Battery			Battery Voltage
	Voltage (V)	Current (A)	Power (W)	(V)
09:00	6.56	4.7	31.1	6.4
10:00	12.22	5.7	70.1	12.0
11:00	12.52	6.3	79.7	12.0
12:00	12.70	5.15	66.3	12.4
13:00	12.95	5.37	68.2	12.6
14:00	12.79	3.3	39.5	12.6
Average	11.62	5.9	59.15	11.33

In addition, the battery voltage increased from 6.4 V at the beginning of the test to 12.6 V at the end of the testing period, as shown in Table 7. This pattern indicates that the battery underwent a charging process from a low-voltage condition toward a near fully charged state. The battery voltage remained relatively stable in the range of 12.0–12.6 V after 10:00, indicating that the solar charge controller was able to maintain the battery charging voltage within a safe operating range, as also evidenced by the voltage values in Table 7.

The relationship between the SCC output voltage to the battery and the battery voltage over time is shown in Fig. 7. Based on Fig. 7, both parameters exhibit similar increasing trends, although a small difference is observed between the SCC output voltage and the actual battery voltage.

To provide an overview of the battery charging

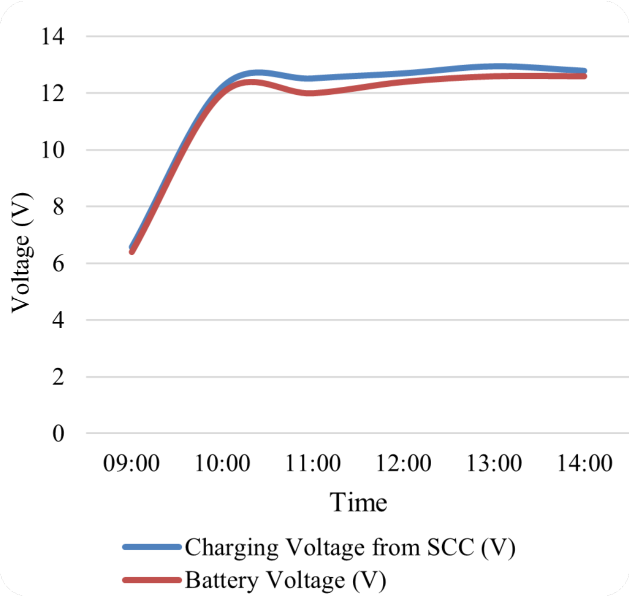

Figure 7: Battery charging voltage characteristics over time.

duration, the charging time was estimated based on the battery capacity and the average charging current. Using a battery capacity of 20 Ah and an average charging current of 5.09 A, and considering a charging efficiency correction factor of 10%, the estimated battery charging time is calculated using (11).

$$t = \frac{C}{I} \times (1+\alpha) \tag{11}$$

where t represents the battery charging time (hours), C is the battery capacity (Ah), I is the average charging current (A), and α is the charging efficiency correction factor. In this study, a correction factor of 10% is applied to represent the charging efficiency of a VRLA battery under field operating conditions, as applied in (11).

Using $C = 20$ Ah, $I = 5.09$ A, and $\alpha = 0.1$, the estimated battery charging time obtained from (11) is:

$$t = \frac{20}{5.09} \times 1.1 = 4.32\,\text{h} \tag{12}$$

The value obtained in (12) indicates that the actual battery charging time is longer than the ideal condition, which is influenced by battery efficiency as well as variations in solar irradiance intensity during the testing process. This estimation provides a more realistic representation of the performance of the off-grid photovoltaic (PV) system in supporting energy storage in the battery.

iii. Inverter and Water Pump Testing

The inverter and water pump testing was conducted using power supplied from a 12 V 20 Ah VRLA battery to evaluate the inverter's capability to convert DC voltage into AC voltage as well as the stability of water pump operation. The test was performed for 30 minutes with specific data acquisition intervals. The observed parameters included voltage, current, and power on the battery side (DC), as well as voltage, current, power factor, and power on the pump motor side (AC).

The results of inverter and water pump testing using battery power are presented in Table 8. Based on Table 8, the battery voltage during the test ranged from 12.20 V to 12.34 V, with an average DC input power of 43.5 W. The current drawn from the battery tended to decrease as the operating time increased, indicating load adjustment and stabilization of system operating conditions. On the AC side, the inverter was able to maintain a relatively stable output voltage in the range of 232–234 V to operate the water pump motor, as summarized in Table 8. The output power of the pump motor recorded an average value of 36.9 W with a relatively constant power factor of 0.27.

Table 8: Inverter and water pump test results using a 12 V 20 Ah battery.

Minute	Battery Measurement (DC)			Pump Motor Measurement (AC)			
	Voltage (V)	Current (A)	Power (W)	Voltage (V)	Current (A)	PF	Power (W)
1	12.34	4.36	53.9	234	0.20	0.27	45.8
5	12.32	3.43	42.2	232	0.16	0.27	35.9
10	12.28	3.43	42.2	232	0.16	0.27	35.9
15	12.25	3.52	43.4	232	0.16	0.27	36.9
20	12.23	3.43	41.9	232	0.15	0.27	35.6
25	12.20	3.29	40.3	232	0.15	0.27	34.3
30	12.20	3.33	40.7	232	0.15	0.27	34.6
Average	12.26	3.54	43.5	232.29	0.16	0.27	36.9

The comparison between the battery input power (DC) and the pump motor output power (AC) over time is shown in Fig. 8. Based on Fig. 8, the DC input power is consistently higher than the AC output power throughout the testing period. The difference between these two power values indicates the presence of conversion losses in the inverter as well as internal power consumption within the system. Nevertheless, the relatively stable power trends on both the DC and AC sides demonstrate that the inverter is capable of operating the water pump continuously without significant fluctuations during the 30-minute testing period, as supported by Table 8 and Fig. 8. Therefore, the selected inverter capacity is considered adequate to support the automatic aquarium water filling system.

iv. Aquarium Water Filling System Performance

The performance testing of the aquarium water filling system was conducted to evaluate the system's capability to automatically fill a 90-liter aquarium using a single-phase water pump supplied by the photovoltaic (PV) system. The observed parameters in this test included filling time, voltage, current, power, power factor, and water flow rate. The test was carried out five

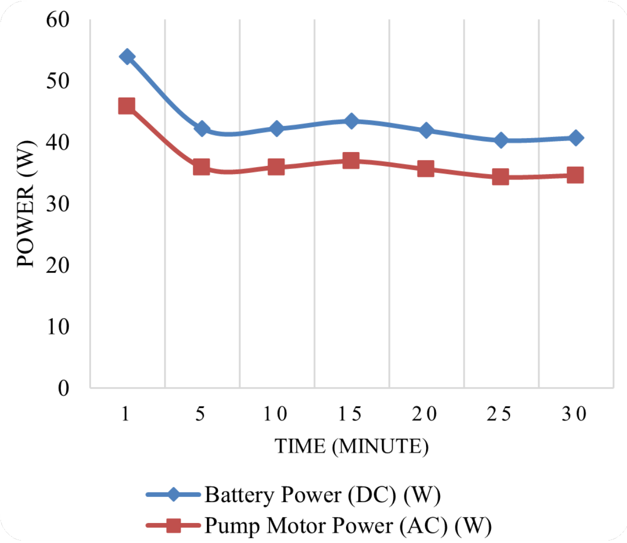

Figure 8: Comparison of DC battery input power and AC water pump motor power over time.

times to assess the consistency of system performance.

The single-phase water pump test results for 90-liter aquarium filling are presented in Table 9. Based on Table 9, the filling time for the 90-liter aquarium ranged from 12.85 to 18.01 minutes. The pump operating voltage remained relatively stable in the range of 232–235 V, with current values between 0.8 and 0.9 A. The electrical power of the pump was recorded in the range of 50.32–56.37 W, indicating that the pump operated close to its nominal power during the filling process. The pump power factor was relatively low, ranging from 0.24 to 0.27, which is a common characteristic of small single-phase induction motor loads, as reflected in Table 9.

Table 9: Single-phase water pump test results for 90-liter aquarium filling.

Test No.	Filling Time (min)	Voltage (V)	Current (A)	Power (W)	PF	Flow Rate (L/min)
1	12.85	235	0.9	50.76	0.24	6.71
2	15.54	234	0.9	50.54	0.24	5.66
3	15.94	234	0.9	50.54	0.24	5.43
4	16.57	233	0.9	50.32	0.24	5.31
5	18.01	232	0.8	56.37	0.27	5.00

The water flow rate produced by the pump showed a decreasing trend as the filling time increased, with flow rate values ranging from 6.71 to 5.00 L/min as shown in Table 9. This decrease in flow rate is caused by the increasing water level inside the aquarium, which results in a higher workload on the pump. The relationship between filling time and water flow rate is shown in Fig. 9, where longer filling durations tend to correspond to lower flow rates, while the total time required to reach a volume of 90 liters increases.

Overall, the test results in Table 9 and Fig. 9 indicate that the photovoltaic (PV)-based automatic aquarium water filling system is capable of operating in a stable and consistent manner. Although variations in filling time and water flow rate were observed in each test, the system was still able to fill the aquarium to the desired volume without manual intervention. These results demonstrate that the proposed system is suitable for small-scale aquarium water filling applications.

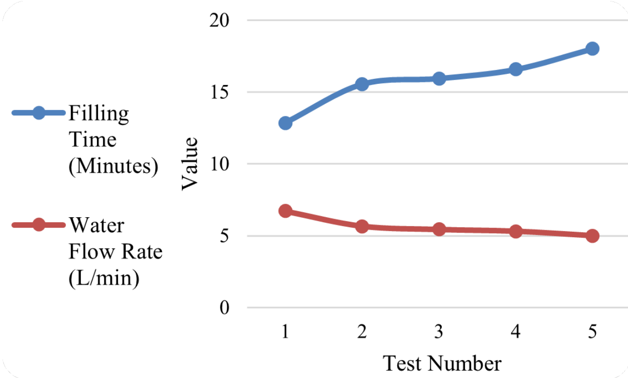

Figure 9: Comparison of filling time and water flow rate during aquarium filling.

v. Analysis of Consumption Reduction

The analysis of PLN electricity consumption reduction was conducted to evaluate the potential utilization of an off-grid photovoltaic (PV) system in replacing conventional electrical energy sources for the aquarium water filling process. Under conventional conditions, a single-phase water pump with an average power of approximately 50 W is operated using electricity supplied from the PLN grid, as indicated by the pump power values reported in Table 9.

Based on the system performance test results in Table 9, the filling time for the 90-liter aquarium ranged from 12.85 to 18.01 minutes per filling cycle. Assuming an average pump operating time of approximately 15 minutes per cycle and a filling frequency of once per day, the electricity consumption from the PLN grid can be estimated using (13).

$$E_{PLN} = P \times t \tag{13}$$

Using $P = 50$ W and $t = 0.25$ h, the estimated daily electricity consumption obtained from (13) is:

$$E_{PLN} = 50 \times 0.25 = 12.5 \text{ Wh/day} \tag{14}$$

Over a one-month period, the daily energy in (14) is equivalent to:

$$E_{month} = 12.5 \times 30 = 375 \text{ Wh} \approx 0.375 \text{ kWh} \tag{15}$$

By implementing an off-grid photovoltaic (PV)-based aquarium water filling system, the electrical energy required for operating the water pump can be fully supplied by solar energy, thereby reducing electricity consumption from the PLN grid for this application, as quantified in (15).

Although the amount of electricity reduction is relatively small, the estimates in (14) and (15) indicate that small-scale photovoltaic (PV) systems have the potential to reduce dependence on PLN electricity for simple household applications that operate on a regular basis. The implementation of similar systems on a larger scale or for multiple aquariums simultaneously has the potential to achieve more significant reductions in electricity consumption.

vi. Uncertainty and Limitations

The results of the photovoltaic (PV) system and aquarium water filling system tests in this study are influenced by several sources of uncertainty and experimental limitations that should be carefully considered when interpreting the findings. The experimental tests were conducted under natural environmental conditions without controlled solar irradiance, which resulted in unavoidable fluctuations in solar irradiance intensity and solar panel surface temperature during the testing period. These environmental variations directly affected the instantaneous power output of the solar panel and the corresponding battery charging rate, as reflected by the changing irradiance, temperature, voltage, and current patterns reported in Table 6. Consequently, the measured PV output parameters represent realistic field operating conditions rather than ideal or laboratory-controlled performance values.

In addition, the solar panel tilt angle was fixed at 15° throughout the entire experimental period, and no solar tracking mechanism was employed. Under this condition, the solar panel could not always maintain an optimal orientation relative to the direction of incident solar radiation, particularly during morning and afternoon periods when the sun's elevation angle varies significantly. As a result, the PV system was not always operated at its maximum power point from a geometric perspective, and the measured output parameters therefore do not fully represent the maximum potential performance of the photovoltaic module. This effect is indirectly implied by the observed fluctuations in output voltage and current reported in Table 6, which are partly attributable to changes in the angle of solar incidence in addition to irradiance and temperature variations.

Measurement uncertainty is also influenced by the intrinsic tolerance and accuracy limitations of the measuring instruments used in this study, including digital multimeters, clamp meters, and solar irradiance meters. Each of these instruments has a finite resolution and measurement error margin that contributes to uncertainty in the recorded voltage, current, power, and irradiance values. Moreover, minor variations in probe placement, cable resistance, and contact quality during data acquisition may have introduced additional small deviations in the measured electrical parameters. For this reason, the experimental data are primarily presented in the form of average values in order to provide a more stable and representative description of overall system performance. This averaging approach was consistently applied to the datasets summarized in Table 6, Table 7, Table 8, and Table 9, thereby reducing the influence of short-term fluctuations and random measurement noise.

In addition to the environmental and instrumentation-related limitations, the performance testing of the automatic aquarium water filling system was conducted using only a single aquarium size with a total volume of 90 liters. While this configuration is representative of a typical household aquarium, it restricts the generalizability of the experimental results to other aquarium capacities, water head levels, and pump power ratings. Different aquarium volumes or pump specifications would alter the hydraulic load conditions, filling duration, electrical power demand, and battery discharge behavior. Therefore, the present results cannot yet be directly extrapolated to larger aquariums or alternative pump configurations without further experimental verification. This limitation is evident from the operating range observed in Table 9 and the filling time versus flow rate trend shown in Fig. 9, which are specific to the tested system configuration.

Furthermore, the experimental evaluation was carried out over a relatively limited observation period and did not include long-term durability testing or seasonal performance assessment. As a result, potential long-term effects such as battery aging, degradation of photovoltaic module efficiency, and variations in system performance under prolonged cloudy or rainy conditions were not captured within the scope of this study. These factors may influence the long-term reliability and energy autonomy of the system when deployed in real household environments.

Overall, while the experimental results provide a realistic and practically relevant representation of system performance under field conditions, the identified sources of uncertainty and the limited scope of system configurations indicate that further development and extended testing are required. Future investigations should include controlled irradiance experiments, variable panel tilt angles or solar tracking mechanisms, a wider range of aquarium sizes and pump capacities, and longer-term monitoring to more comprehensively evaluate system robustness and scalability under diverse environmental and operational conditions.

IV. Conclusion

Based on the results of the design, implementation, and testing of the off-grid photovoltaic (PV)-based automatic aquarium water filling system, several conclusions can be drawn as follows:

1. The 100 Wp off-grid photovoltaic (PV)-based automatic aquarium water filling system was successfully implemented and operated as designed. All main components, including the solar panel, solar charge controller, battery, inverter, water pump, and water level sensor, were well integrated into a single system that functions automatically, as demonstrated by the implementation results shown in Fig. 5.
2. The no-load photovoltaic (PV) system test results show that the solar panel output is influenced by variations in solar irradiance intensity. The panel output current increases with increasing irradiance, while the panel voltage remains relatively stable within the operating range of a 12 V PV system, as summarized in Table 6 and visualized in Fig. 6. The battery charging process can operate stably under the regulation of the solar charge controller, as evidenced by Table 6 and Table 7.
3. The battery charging characteristics indicate that the 12 V 20 Ah VRLA battery can be charged effectively, with an average charging current of approximately 5 A. The estimated battery charging time of 4.32 hours reflects a more realistic charging condition by considering battery efficiency and variations in solar irradiance intensity, as quantified in (12) and supported by the trends shown in Fig. 7.
4. The inverter and water pump testing using battery power shows that the inverter is capable of converting DC voltage into AC voltage stably to operate the water pump. The DC input power from the battery is higher than the AC output power at the pump motor, indicating the presence of conversion losses; however, the system is still able to operate continuously without interruption, as reported in Table 8 and illustrated in Fig. 8.
5. The automatic aquarium water filling system is capable of filling a 90-liter aquarium with a filling time ranging from 12.85 to 18.01 minutes and a water flow rate of 5.00–6.71 L/min. These results indicate that the system demonstrates reliable and consistent performance for small-scale aquarium water filling applications, as shown in Table 9 and Fig. 9.
6. The application of an off-grid photovoltaic (PV) system for aquarium water filling has the potential to reduce electricity consumption from the PLN grid, particularly for simple household applications that operate on a regular basis, although the magnitude of electricity reduction is relatively small, as estimated in (15).

Based on the results of the study, several recommendations for future development are proposed as follows:

1. Future studies are recommended to use a more optimal solar panel tilt angle or to implement a solar tracking system in order to increase the electrical energy generated by the solar panel.
2. System testing can be further developed by using different aquarium capacities and pump types to determine the system's performance limits and to improve the generalizability of the research results.
3. The use of a maximum power point tracking (MPPT) solar charge controller can be considered in future studies to compare the system performance and efficiency with the PWM-type SCC used in this study.
4. Further analysis of economic aspects, such as investment costs, operational costs, and potential long-term PLN electricity savings, can be conducted to provide a more comprehensive assessment of system feasibility.
5. The integration of sensor-based monitoring systems and real-time data logging is recommended to obtain more detailed experimental data and to improve the accuracy of system performance analysis.

References

[1] S. Suratno and B. D. Cahyono, "Rancang bangun sistem pembangkit listrik tenaga surya (plts) sebagai catu daya pompa air submersible," *Jurnal Teknik Elektro Uniba (JTE UNIBA)*, vol. 7, no. 2, pp. 309–319, 2023. https://doi.org/10.36277/jteuniba.v7i2.220

[2] Z. Arifin, A. J. Tamamy, and N. Islahu, "Perancangan mesin pompa air tenaga surya untuk mengurangi konsumsi listrik skala rumahan," *Jurnal Nasional Teknik Elektro*, vol. 9, no. 2, p. 79, 2020. https://doi.org/10.25077/jnte.v9n2.758.2020

[3] Samsurizal, Mauriraya, K. T., M. Fikri, N. Pasra, and Christiono, *Buku PLTS*, 2021, pDF.

[4] A. G. Hutajulu, M. R. T. Siregar, and M. P. Pambudi, "Rancang bangun pembangkit listrik tenaga surya (plts) on grid di ecopark ancol," *TESLA: Jurnal Teknik Elektro*, vol. 22, no. 1, p. 23, 2020. https://doi.org/10.24912/tesla.v22i1.7333

[5] J. Teknik and T. Listrik, "Perancangan dan analisis tenaga surya sistem pompa air," vol. 11, no. November, pp. 92–100, 2020. https://doi.org/10.34218/IJEET.11.9.2020.009

[6] V. Gunasekaran and S. Chakraborty, “Technical and environmental aspects of solar photo-voltaic water pumping systems: a comprehensive survey,” *Water Supply*, vol. 23, no. 7, pp. 2676–2710, 2023. https://doi.org/10.2166/ws.2023.165

[7] R. J. Chilundo, U. S. Mahanjane, and D. Neves, “Design and performance of photovoltaic water pumping systems: Comprehensive review towards a renewable strategy for mozambique,” 2018. https://doi.org/10.4236/JPEE.2018.67003

[8] S. Sharma, A. Tomar, and V. Bhagat, “Pv-based water pumping system—a comprehensive review,” 2020. https://doi.org/10.1007/978-981-15-5463-6_34

[9] T. T. Chiagunye, S. F. Ilo, G. I. Ndukwe, H. U. Udeani, and O. D. Okey, “Development of an automated aquarium monitoring system with an iot interface using google sheets,” *ABUAD Journal of Engineering Research and Development (AJERD)*, vol. 8, no. 2, pp. 66–74, 2025. https://doi.org/10.53982/ajerd.2025.0802.07-j

[10] C. L. Kok, C. K. Ho, N. Tanjodi, and Y. Y. Koh, “A novel water level control system for sustainable aquarium use,” *Electronics*, vol. 13, no. 11, p. 2033, 2024. https://doi.org/10.3390/electronics13112033

[11] J. London, “Embedded microcontrol for photovoltaic water pumping system,” *arXiv*, 2025. https://doi.org/10.48550/ARXIV.2508.06708

[12] A. Sarwar and M. T. Iqbal, “Solar powered water pumping system automation and control using a microcontroller for aquaculture,” *European Journal of Electrical Engineering and Computer Science*, vol. 6, no. 4, pp. 17–22, 2022. https://doi.org/10.24018/ejece.2022.6.4.447

[13] A. N. Fey, V. Leite, and E. F. Ribeiro Romaneli, “A low power photovoltaic water pumping system based on a dc–dc step-up converter and standard frequency converters,” in *2020 9th International Conference on Renewable Energy Research and Application (ICRERA)*. IEEE, 2020, pp. 138–143. https://doi.org/10.1109/ICRERA49962.2020.9242833

[14] S. D. A. Febriani, A. M. Alqarana, M. J. Wibowo, and A. Fahriannur, “Assessing the performance of off-grid solar photovoltaic power plants in supporting aquaponics systems,” *PENA TEKNIK: Jurnal Ilmiah Ilmu-Ilmu Teknik*, pp. 54–65, 2024. https://doi.org/10.51557/pt_jiit.v9i1.2170

[15] M. Masthura and A. Armansyah, “Utilization of solar panels as a source of electrical energy in alternating current (ac) water pump,” *Jurnal Fisika Flux: Jurnal Ilmiah Fisika FMIPA Universitas Lambung Mangkurat*, vol. 20, no. 1, p. 38, 2023. https://doi.org/10.20527/flux.v20i1.14421

[16] L. H. Lubis, M. Mesyadi, and M. I. Nasution, “Integration of solar panels and arduino for aquaponic system automation and solar energy efficiency,” *Indonesian Physical Review*, 2024. https://doi.org/10.29303/ipr.v8i1.415

[17] I. F. Alam, A. Azis, P. Surya, and S. P. District, “Perencanaan pembangkit listrik tenaga surya (plts) untuk pompa irigasi sawah di desa ulak aurstanding kecamatan pemulutan selatan kabupaten ogan ilir izzul,” vol. 8, no. 1, pp. 1–11, 2023.

[18] A. F. Dalimunthe, S. T. Rahmaniar, and S. Anisah, “Perancangan solar charge controller (scc) pada pembangkit listrik tenaga surya 600 wp untuk rumah tinggal,” vol. 5, pp. 5–6, 2021.

[19] L. Jacobus, E. Setyowati, E. N. S. Patty, and F. Bokol, “Desain sistem pompa air tenaga surya,” *Elektriese: Jurnal Sains dan Teknologi Elektro*, vol. 13, no. 1, pp. 1–8, 2023. https://doi.org/10.47709/elektriese.v13i01.2283

[20] S. K. Bhosale, “Pengembangan pompa submersible bertenaga surya sistem tanpa penggunaan baterai dalam pertanian,” *Jurnal Pendidikan Indonesia Penelitian dan Teknologi*, vol. 2, no. 1, pp. 57–64, 2022.

[21] B. Dilla, B. Widi, S. Wilyanti, A. Jaenul, Z. M. Antono, and A. Pangestu, “Implementasi solar charge controller untuk pengisian baterai dengan menggunakan sumber energi hybrid pada sepeda motor listrik,” *Jurnal Edukasi Elektro*, vol. 6, no. 2, pp. 128–135, 2022. https://doi.org/10.21831/jee.v6i2.53327