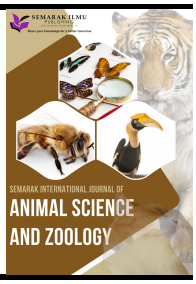
Semarak International Journal of Animal Science and Zoology

Journal homepage:

https://semarakilmu.my/index.php/sijasz/index

ISSN: 3083-9254



Design of a Solar-Powered Esp32-Based Automatic Fish Feeding System for Sustainable Small-Scale Aquaculture

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ARTICLE INFO

Article history:
Received 22 August 2026
Received in revised form 21 September 2026
Accepted 30 September 2026
Available online 28 October 2026

Keywords:
Automatic Fish Feeder; Solar Energy; ESP32, Aquaculture; Photovoltic System; Renewable Energy

ABSTRACT

Efficient feed management is an important part of small-scale aquaculture because feeding that is not properly controlled can result in excessive feed use and unnecessary wast. This study presents the design of a solar-powered automatic fish feeding system for pond and tank aquaculture. The system is designed to provide fish feed at scheduled times while reducing dependence on grid electricity, particulary in areas with limited access to electrical infrastructure. The proposed system consists of a 30 Wp photovoltaic panel, a 12 V 7 Ah sealed lead-acid (SLA) battery, a PWM solar charge controller, an ESP32 microcontroller, an MG996R servo motor, and an I2C LCD. The photovoltaic panel serves as the main energy source and charges the battery through the solar charge controller. The stored energy is then used to operate the control and feeding schedule and controls the servo motor to open and close the feed dispenser according to the programmed settings. The system was developed using an engineering research approach involving system design, component assembly, and functional evaluation. Based on the system design, the estimated energy consumption is approximately 3.6 Wh per day, allowing the system to operate with renewable energy demand. The proposed design combines automatic feeding with renewable energy, providing a practical alternative for small-scale aquaculture operations, especially in locations where access to grid electricity is limited.

1. Introduction

Small-scale fish farming is one of the important sectors in providing protein sources and supporting the economy, especially in rural areas and areas with limited access to infrastructure. One of the operational aspects that greatly affects the success of aquaculture is feed management. Feeding that is carried out manually and without a consistent schedule can lead to overfeeding and underfeeding [1]. Overfeeding not only increases operational costs due to wasted feed but can also reduce pond water quality due to the accumulation of feed residues and unabsorbed metabolic products, which can ultimately trigger the growth of pathogenic microorganisms and reduce the survival rate of fish.

To overcome these problems, various studies have developed automatic fish feeding systems based on microcontrollers with fixed-time scheduling, which are able to dispense feed consistently without manual involvement [2][3]. Subsequent developments have integrated Internet of Things (IoT) connectivity so that feeding schedules can be monitored and controlled remotely through

mobile applications. In addition, to overcome the limitations of access to grid electricity in remote pond locations, several studies have integrated renewable energy sources in the form of solar panels as an off-grid power supply for feeding systems and ESP32-based aquarium/pond water quality monitoring systems [4].

Most previous studies have focused on systems with complex sensor monitoring features (temperature, pH, and turbidity) and have used large-capacity solar panels and batteries, which tend to increase investment costs [5][6]. On the other hand, limited research has systematically designed solar-powered automatic feeding systems with low power requirements and clear energy budget calculations so that their operational feasibility based on solar energy availability in the tropics can be determined from the design stage. This gap drives the need for research on the design of ESP32-based solar-powered automatic fish feeding systems that are simple, power-efficient, and suitable for small-scale fish farming [7].

This research aims to design and implement a prototype of an ESP32-based solar-powered automatic fish feeding system and evaluate the energy requirements of the system compared to the potential energy that can be generated by solar panels and stored in batteries [8][9]. Technically, this research contributes energy budget design and calculation data that can be used as a reference for developing similar systems. Socially, this system is expected to help small-scale fish farmers in areas with limited access to electricity implement more consistent and cost-effective feeding systems while supporting the use of renewable energy in the aquaculture sector.

2. Methodology

This research uses an engineering design research approach consisting of three main stages: system design, component assembly, and functional evaluation. In the system design stage, a system block diagram is developed to depict the energy flow and control flow. The photovoltaic panel generates electrical energy that is channeled through a PWM-type solar charge controller (SCC) to charge a 12 V, 7 Ah SLA battery. The energy from the battery is then used to supply the ESP32, which functions as a control unit and scheduler (using a real-time reference). The ESP32 drives the MG996R servo motor to open and close the feed container according to a programmed schedule and displays the system status and next feeding time on the I2C LCD.

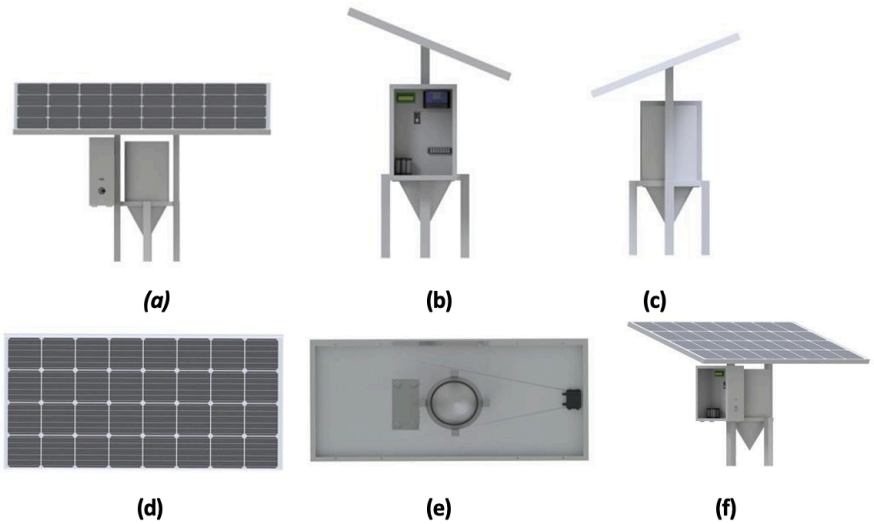


Fig. 1. Prototype Design of Solar-Powered Automatic Fish Feeding System: (a) Front View, (b) Left Side View, (c) Right Side View, (d) Top View, (e) Bottom View, and (f) Perspective View

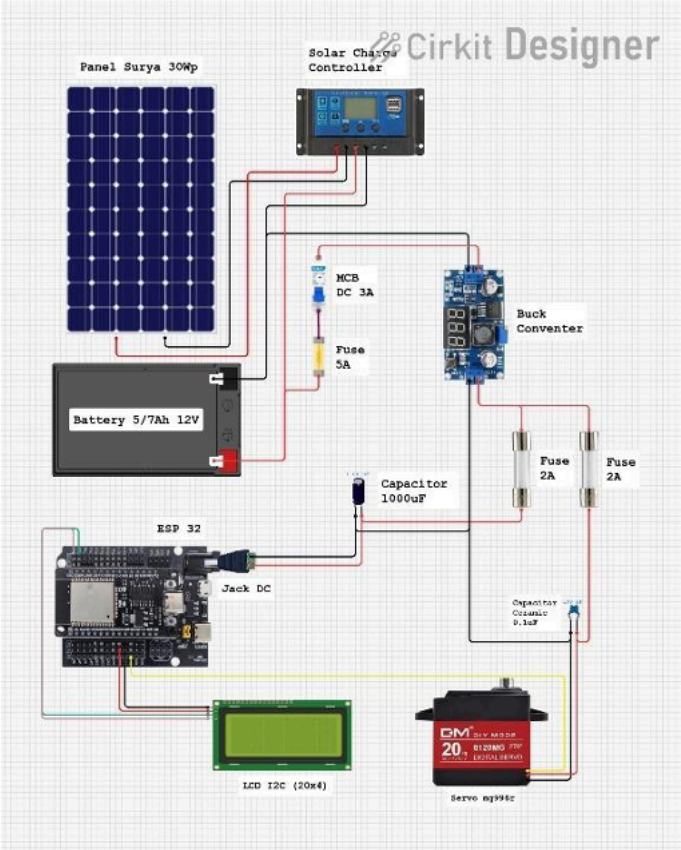


Fig. 2. Wiring Diagram of the Solar-Powered Automatic Fish Feeder System

Figure 2 shows the interconnection scheme between the electronic components in greater detail. The 30 Wp solar panel is connected to a solar charge controller (SCC) to charge a 12 V/7 Ah SLA battery. From the battery, the voltage is supplied through the 3 A DC MCB as the main safety device and a 5 A fuse to the buck converter, which lowers the voltage to the appropriate level to supply the ESP32 through the DC jack. A 1000 µF capacitor functions as a voltage stabilizer. The buck converter output is also routed through two 2 A fuses to the MG996R servo motor, with a 0.1 µF ceramic capacitor for switching noise reduction on the aquarium side.

Furthermore, the ESP32 controls the servo motor according to a pre-programmed schedule and displays the system status on the I2C 20×4 LCD.

The design goal is to develop a small-scale prototype suitable for ponds or household aquaculture ponds. Data collection is carried out in two ways: (1) reviewing the technical specifications (datasheets) of each component to obtain voltage, current, and nominal power parameters, and (2) conducting functional testing at the prototype stage (bench test) to verify the consistency between the scheduling logic design and actuator performance and the expected results. Table 1 summarizes the specifications of the main components used in the system.

Table 1
Specifications of the Main Components of the System

Components	Specification	Functions in the System
Photovoltaic (PV) panels	Monocrystalline, 30 Wp, 12 V	Main energy source of the system
Solar charge controller	PWM type, 12 V / 10 A	Regulates battery charging and prevents overcharging/overdischarging
Battery	Sealed Lead-Acid (SLA), 12 V, 7 Ah	Operational backup energy storage
Microcontroller	ESP32 DevKit	Control unit and feeding time scheduler
Servo motor	MG996R	Feed mechanism opening/closing actuator
Display	20×4 I2C LCD	System status indicators and feeding schedule

Data analysis in this study was carried out by calculating the daily energy budget of the system based on the electrical parameters of each component and comparing it with the estimated energy that can be harvested by solar panels using the peak sun hour (PSH) method, which is commonly used in the design of standalone photovoltaic systems. Furthermore, battery autonomy analysis was carried out to determine how long the system could operate without solar energy input. The calculation results were further verified through functional testing on the prototype to ensure that the scheduling and actuation mechanisms operated according to the design.

3. Results

3.1 Estimating System Energy Requirements

The estimated daily energy consumption of the system is calculated based on the average power and effective operating time of each electronic component, as presented in Table 2. The ESP32 is assumed to operate in a duty-cycle pattern between standby mode (deep sleep) and Wi-Fi active mode/scheduled processing throughout the day. The servo motor is active only for a short period during feeding (three times a day, approximately 10 seconds each), while the LCD remains on continuously as a status indicator.

Table 2
Estimated Daily Energy Consumption of the System

Components	Voltage (V)	Estimated Average Power (W)	Effective Operating Time (hours/day)	Energy (Wh/day)
ESP32 (standby + scheduled active)	5	0.10	24	2.40
MG996R servo motor (3 feeding times of 10 seconds each)	5	5.0	0.008	0.04
I2C 16×2 LCD (status indicator)	5	0.05	24	1.20
Total estimated daily energy requirement	–	–	–	3.64 (≈ 3.6)

The calculations show that the total energy requirement of the system is approximately 3.6 Wh per day, which is consistent with the initial estimate at the design stage. This value is relatively low compared to similar systems equipped with multiple sensors and continuous communication modules, as the main load of this system consists only of a scheduler control unit, one servo actuator, and one LCD display.

3.2 Solar Panel Energy Availability Estimation

Assuming tropical climate conditions such as those in Malang, East Java, with an average effective peak sun hour of approximately 4 hours per day and a system derating factor of 0.75 to account for cable losses, panel operating temperature, dust accumulation, and the conversion efficiency of the PWM-type solar charge controller, the energy that can be harvested by a 30 Wp solar panel per day can be estimated as follows:

$$E_{PV} = P_{panel} \times PSH \times faktor\ derating = 30\ Wp \times 4\ hour \times 0{,}75 \approx 90\ Wh/day$$

The estimated solar energy yield (≈90 Wh/day) far exceeds the system's energy requirements (≈3.6 Wh/day), with a margin of approximately 25 times. This large margin indicates that the selected solar panel capacity provides sufficient safety reserves to accommodate several consecutive days of low solar radiation intensity (cloudy or rainy conditions), while also providing opportunities for further development, such as adding water quality sensors or IoT communication modules without significantly increasing the solar panel capacity.

3.3 Battery Autonomy Analysis

An SLA battery with a capacity of 12 V and 7 Ah stores 84 Wh (12 V × 7 Ah) of energy. Assuming the worst-case condition in which there is no energy input from the solar panel, the theoretical battery autonomy for a load of 3.6 Wh/day is:

$$Otonomi\ teoritis = 84\ Wh \div 3{,}6\ Wh/day \approx 23\ day$$

However, to maintain the lifespan of the SLA battery, the safe depth of discharge (DoD) is generally limited to approximately 50%. Therefore, the practical battery autonomy is approximately 11–12 days without recharging. This autonomy value far exceeds normal operational requirements, considering that solar panels routinely recharge the battery daily under normal weather conditions, thereby maintaining system reliability during unfavorable weather conditions.

3.4 Prototype Functional Testing

Functional testing was carried out at the prototype stage (bench test) to verify the compatibility between the scheduling logic of the ESP32, servo motor actuation, and LCD indicator and the predetermined design. The test scenarios and results are presented in Table 3.

Table 3
Prototype Functional Test Scenarios and Results

No.	Testing Scenarios	Expected Results	Observation Results
1	ESP32 reaches the scheduled feeding time (3 times/day)	The servo motor opens the feed container for approximately 2 seconds	Conform
2	The duration of the feed container opening has elapsed	The servo motor reseals the feed container	Conform
3	The system operates normally	The LCD displays the status and schedule of the next feeding	Conform

4	Solar panels do not receive light (nighttime)	The system continues operating the feeding cycle using battery energy	Conform
5	Simulation of consecutive cloudy conditions (sci-test)	The battery supplies the required energy without a sudden system shutdown	Conform

It should be emphasized that the functional testing carried out in this study involved verification of the control logic and actuator mechanism at the prototype scale (bench test) over a limited period, rather than long-term field testing in an actual aquaculture pond under seasonal weather variations. Therefore, the test results demonstrate the functional feasibility of the design, but validation of long-term performance under actual field conditions is still required.

3.5 Discussion

Compared to the studies by Faiz et al. and Tomas et al., who designed solar-powered feeding systems with larger-capacity panels (100 Wp), lithium batteries, and MPPT controllers to support IoT connectivity and continuous monitoring, the design in this study deliberately uses a smaller-capacity solar panel (30 Wp) with a simpler and more economical PWM-type solar charge controller. This choice is based on the much lower system load, as it does not involve a sensor network or continuous data transmission. Therefore, the system can still provide a large energy margin despite using lower-power components. The combination of a 30 W panel and a 12 V SLA battery in this study is also consistent with the power supply configuration used by Chiagunye et al. in an ESP32-based aquarium monitoring system, which shows that this capacity is adequate for small-scale microcontroller and actuator loads.

Compared to microcontroller-based feeding systems that rely solely on grid power supplies or batteries that must be replaced or charged manually, the addition of solar energy to this system eliminates dependence on grid electrical infrastructure and manual intervention for charging, making it more suitable for ponds located far from electricity access. It also indirectly addresses the problem of inconsistent manual feeding, which can lead to water quality degradation due to excess feed residues, because the feeding schedule is controlled automatically and consistently by the ESP32 without requiring continuous human presence.

However, this study still has limitations because the performance evaluation was carried out only through design calculations and prototype-scale functional testing. It did not include multi-week field testing in actual ponds under variations in seasonal solar radiation intensity or feedback mechanisms such as feed level sensors or water quality sensors, as implemented in more complex systems [1]. These aspects provide opportunities for development in future research.

4. Conclusions

4.1 Conclusion

This study successfully designed and implemented a prototype of an ESP32-based solar-powered automatic fish feeding system consisting of a 30 Wp photovoltaic panel, PWM solar charge controller, 12 V 7 Ah SLA battery, MG996R servo motor, and I2C LCD. The calculation results showed that the system's energy requirement was approximately 3.6 Wh per day, much lower than the estimated energy that the solar panel could produce (approximately 90 Wh/day), thus providing a large reliability margin. The 84 Wh battery capacity was also able to provide operational backup autonomy for several days without solar energy input. Functional testing at the prototype stage showed that the ESP32 scheduling mechanism, servo motor actuation, and LCD indicator operated according to

the intended design. Thus, the proposed system is worthy of consideration as a cost-effective, energy-efficient, and energy-independent automatic fish feeding solution for small-scale fish farming, especially in locations with limited access to grid electricity.

4.2 Suggestions

Further research is recommended to conduct long-term field testing in actual aquaculture ponds to validate the system's performance under seasonal weather variations. In addition, it is recommended to incorporate feed level and basic water quality monitoring sensors (temperature and pH), as used in similar studies; integrate IoT connectivity and mobile applications for remote control and monitoring, as implemented in previous studies; and conduct an economic feasibility study comparing investment costs with potential operational savings if the system is implemented on a wider scale.

Acknowledgments
The author would like to thank the D-IV Power Plant Engineering Study Program, Vocational Faculty, State University of Malang, for the facilities, academic guidance, and support provided during the implementation of this research.

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