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Design of a Solar-Powered ESP32-Based Automatic Fish Feeding System for Sustainable Small-Scale Aquaculture

Iltizamul Haqqi[1,*], Devina Aprillia[1], Dava Maulana Yudha[1]

[1] Department of Engineering Technology, Power Plant Engineering Technology, Fakulti of Vocational, State University of Malang, 65145 Malang, Jawa Timur, Indonesia

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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 the provision of protein sources and is a support in the economic sector, 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 unscheduled consistently can lead to overfeeding and underfeeding[1]. Overfeeding conditions not only increase operational costs due to wasted feed, but can also reduce pond water quality due to the accumulation of feed residues and unabsorbed metabolic results, which can ultimately trigger the growth of pathogenic microorganisms and reduce the survival rate of fish.

* *Corresponding author.*
E-mail address: iltizamul.haqqi.2309346@students.um.ac.id

To overcome the problems that occur, various studies have developed an automatic fish feeding system by developing an automatic fish feeding device based on a microcontroller with fixed time scheduling, which is able to describe feed consistently without manual involvement[2][3]. Subsequent developments integrate 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 network electricity access 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].

Although most previous research has focused on systems with complex sensor monitoring features (temperature, pH, turbidity) and using solar panel capacity and large power batteries that tend to increase investment costs[5][6]. On the other hand, research that systematically designs solar-powered automatic feeding systems with low power requirements along with clear energy budget calculations, so that its operational feasibility for the availability of solar energy in the tropics can be ascertained from the design stage. This gap is what drives the need for research on the design of ESP32-based solar automatic fish feeding systems that are simple, power-efficient, and suitable for small-scale fish farming needs[7].

This research aims to design and implement a prototype of an ESP32-based solar automatic fish feeding system, as well as evaluate the energy needs of the system compared to the potential energy that can be generated by solar panels and stored by batteries[8][9]. Technically, this research contributes in the form of energy budget design and calculation data that can be used as a reference for the development of similar systems. Socially, this system is expected to help small-scale fish farmers in areas with limited access to electricity to implement more consistent and cost-effective feeders, 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, namely system design, component assembly, and functional evaluation. In the system design stage, a system block diagram is determined that depicts 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 as a control unit and scheduler (using real-time reference), which further drives the MG996R servo motor to open and close the feed container according to a programmed schedule, as well as display the system status and subsequent feeding time on the I2C LCD.

Figure 2 shows the interconnection scheme between the electronic components in more 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 transmitted through the MCB DC 3A as the main safety and the 5A fuse goes to the buck conventer which lowers the voltage to the appropriate level to supply the ESP32 through the DC jack, with a 1000 µF capacitor that functions as the voltage stabilizer, the buck converter output is also routed through two 2A fuses to the MG996R servo motor, with a 0.1 µF ceramic capacitor as a 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 12C 20x4 LCCD. The design goal is a prototype of a small-scale system suitable for kolan or household aquaculture ponds. The data collection technique is carried out in two ways, namely (1) a study of the technical specifications (datasheet) of each component to obtain voltage, current, and nominal power parameters, and (2) functional testing at the prototype stage (bench test) to verify the suitability between the design of the scheduling logic and

the performance of the actuator with the expected results. Table 1 summarizes the specifications of the main components used in the system.

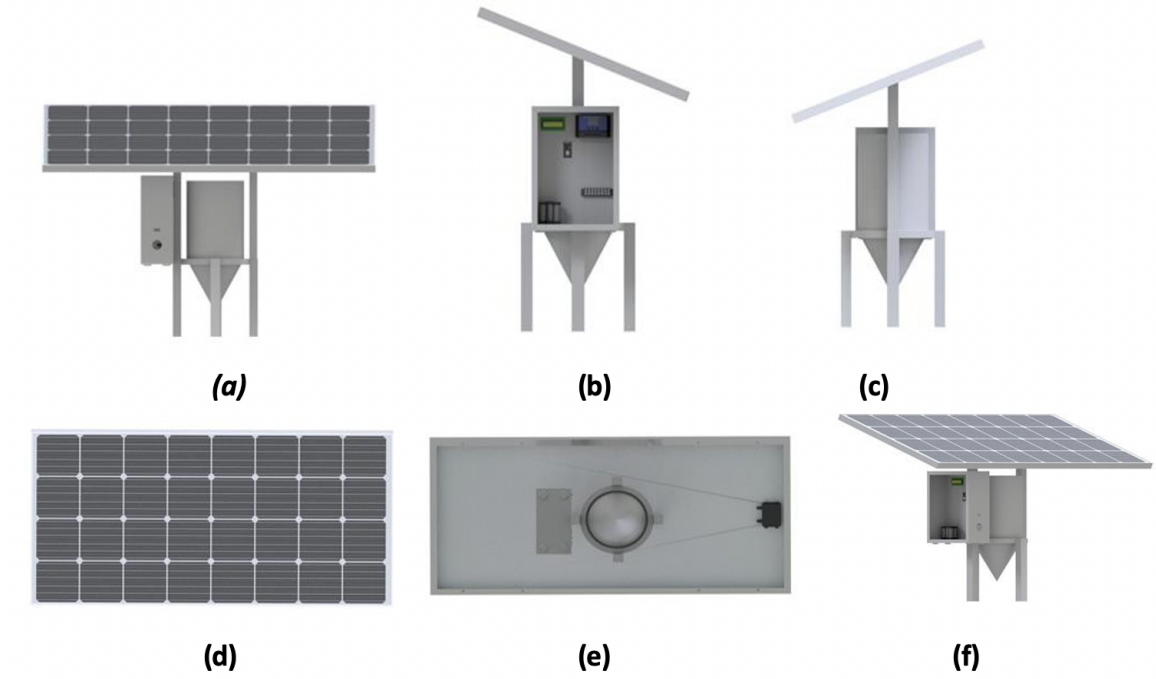

Fig. 1. Prototype Design of Solar Powered Automatic Fish Feeding System (a) Front View (b) Left Side View (c) Right Side View (d) Top View (e) Bottom View (f) Perspective View

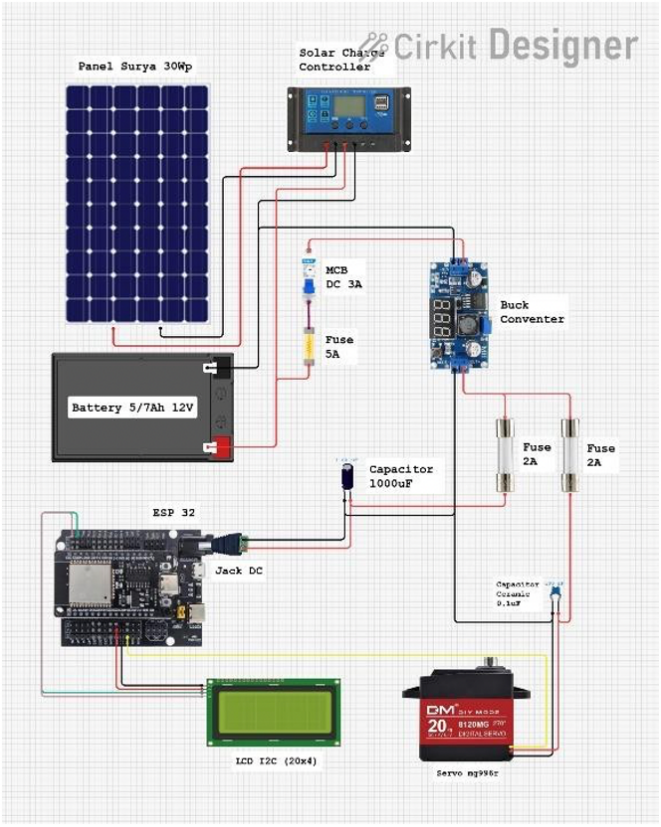

Fig. 2. Wiring diagram of solar powered automatic fish feeder system

Table 1
Specifications of the Main Components of the System

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

The data analysis technique in this study was carried out through the calculation of the daily energy budget of the system based on the electrical parameters of each component, then compared with the estimate of energy that can be harvested by solar panels using the peak sun hour (PSH) method which is commonly used in the design of independent photovoltaic systems. Furthermore, battery autonomy analysis was carried out to determine the length of time the system can operate without solar energy input. The results of the calculation were further verified through functional testing on the prototype to ensure that the scheduling and actuation mechanism runs according to 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 work in a duty-cycle pattern between standby mode (deep sleep) and Wi-Fi active mode/scheduled processing throughout the day, while the servo motor is only active for a short time at the time of feeding (three times a day, each about 10 seconds), and the LCD is on continuously as a status indicator.

Table 2
Estimated Daily Energy Consumption System

Components	Voltage (V)	Estimated Average Power (W)	Effective Operating Time (hours/day)	Energy (Wh/day)
ESP32 (standby and scheduled active operation)	5	0.10	24	2.40
MG996R servo motor (3 feeding cycles, 10 seconds each)	5	5.00	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 about 3.6 Wh per day, which is in line with the initial estimate at the design stage. This value is relatively low compared to similar systems equipped with many sensors and continuous communication modules, as the main load of this system is only in the form 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 in Malang, East Java, which has an average effective peak sun hour of about 4 hours per day, as well as a system derating factor of 0.75 to take into account cable loss, panel operating temperature, dust accumulation, and conversion efficiency of PWM type solar charge controller, the energy that can be harvested by a solar panel of 30 Wp 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 value of solar energy yield (≈90 Wh/day) far exceeds the system's energy needs (≈3.6 Wh/day), with a margin of about 25 times. This large margin indicates that the selected solar panel capacity provides sufficient safety reserves to anticipate several consecutive days with low solar radiation intensity (cloudy/rainy), while opening up further development opportunities such as the addition of water quality sensors or IoT communication modules without the need to significantly increase the capacity of solar panels.

3.3 Battery Autonomy Analysis

An SLA battery with a capacity of 12 V 7 Ah stores 84 Wh (12 V × 7 Ah) energy. If the worst condition is assumed to be no energy input from the solar panel at all, then the theoretical autonomy of the battery to a load of 3.6 Wh/day is

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

However, to maintain the life of the SLA battery, a safe depth of discharge (DoD) is generally limited to around 50%, so the practical autonomy of the battery is about 11-12 days without recharging. This autonomy value far exceeds normal operational needs, considering that solar panels routinely recharge the battery daily under normal weather conditions, so that the system's reliability against less favorable weather can be maintained.

3.4 Prototype Functional Testing

Functional testing is carried out at the prototype stage (bench test) to verify the compatibility between the scheduling logic on the ESP32, servo motor actuation, and LCD indicator with 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 specified duration for opening the feed container has elapsed.	The servo motor closes and reseals the feed container.	Conform
3	The system operates normally.	The LCD displays the system status and the next scheduled feeding time.	Conform
4	Solar panels do not receive sunlight (nighttime conditions).	The system continues operating the feeding cycle using energy stored in the battery.	Conform
5	Simulation of consecutive cloudy conditions (simulation test).	The battery supplies the required energy without causing an unexpected system shutdown.	Conform

It should be emphasized that the functional testing carried out in this study is a verification of the control logic and actuator mechanism on a prototype scale (bench test) in a limited time, not a long-term field test on a real cultivation column with seasonal weather variations. Therefore, the results of this test show the functional feasibility of the design, but validation of long-term performance in actual field conditions is still needed.

3.5 Discussion

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

Compared to microcontroller-based feeding systems that rely only on grid power supplies or batteries that must be replaced/charged manually, the addition of solar energy sources to this system eliminates dependence on grid electrical infrastructure and manual intervention for charging, making it more suitable to be applied to ponds or ponds located far from electricity access. It also indirectly answers the problem of inconsistency in manual feeding that can trigger water quality degradation due to excess feed residue, because the feeding schedule is controlled automatically and consistently by ESP32 without relying on human presence at all times.

However, this study still has limitations because the performance evaluation is only carried out at the design calculation stage and prototype-scale functional testing, does not include multi-week field testing on real ponds with variations in the intensity of seasonal solar radiation, nor feedback mechanisms such as feed level sensors or water quality sensors as have been applied to more complex systems [1]. These aspects are 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 energy requirement of the system was about 3.6 Wh per day much smaller than the estimated energy that the solar panel could produce (±90 Wh/day), thus providing a large margin of reliability. 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 worked according to the set 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 on actual ponds or aquaculture ponds to validate the system's performance against actual seasonal weather variations. In addition, it is also recommended to add feed level and baseline water quality monitoring sensors (temperature and pH) referring to similar studies, integrate IoT connectivity and mobile applications for remote control and monitoring as has been applied in previous studies and conduct an economic feasibility study in the form of comparing investment costs with potential operational savings if this system is implemented on a wider scale.

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