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Design and Implementation of a Solar-Powered IoT Smart Fish Feeder for Sustainable Freshwater Aquaculture

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Abstract

The utilization of solar energy in aquaculture automation still encounters challenges related to energy efficiency, stability, and adaptive control within IoT-based systems. This research presents the design and implementation of a solar-powered IoT Smart Fish Feeder, developed to enable adaptive feeding schedules with optimized power management. The system is composed of a 100 Wp solar panel, a 25 A MPPT charge controller, a 14.8 V lithium battery, a 2P DC MCB (440 V/25–16 A), and an APZEM-017 ModBus DC wattmeter, integrated with a DC–DC Boost Converter to regulate power delivery for the feeder prototype. Experimental tests were conducted to evaluate solar energy performance under real environmental conditions, focusing on parameters such as voltage, current, power output, and energy conversion efficiency. Results demonstrated that the solar panel achieved an average conversion efficiency of 87.2%, the MPPT controller maintained an efficiency of 95%, the battery system reached a charge–discharge efficiency of 90.4%, and the DC–DC converter operated at 92% efficiency, resulting in an overall system efficiency of 68.8%. The system maintained voltage stability within ±2% and was capable of autonomous 24-hour operation without external power. Compared to previous studies that lacked solar–IoT integration and adaptive control, this prototype provides a novel and energy-efficient solution for sustainable aquaculture. The findings confirm that the proposed design enhances renewable energy utilization, operational reliability, and environmental sustainability in innovative aquaculture applications.

Keywords: adaptive feeding schedule, energy efficiency, green IoT, smart fish feeder, solar energy, sustainable aquaculture

1. Introduction

The aquaculture sector is currently a crucial pillar of global food security, playing a vital role in meeting the demand for sustainable and environmentally friendly animal protein [1]. According to a report by the Food and Agriculture Organization (FAO), aquaculture production continues to increase in line with human population growth. Still, this increase is often accompanied by rising energy consumption and operational costs [2]. In freshwater fish farming systems, the feeding process is a dominant activity, accounting for more than 60% of total operational costs [3]. Inefficiencies in this process not only result in wasted electrical energy but also reduce fish growth efficiency and pond productivity [4]. Therefore, the application of renewable energy sources, particularly solar energy, is a strategic solution to reduce dependence on conventional electricity supplies and reduce carbon emissions in fisheries automation systems [5].

Several previous studies have explored the application of the Internet of Things (IoT) in feeding system automation, enabling remote control and monitoring using wireless networks and smart sensors [6-8]. This technology has been demonstrated to enhance feed management efficiency, minimize distribution delays, and offer real-time water condition monitoring capabilities [9]. However, most systems still rely on conventional energy supplies such as grid electricity (PLN) or standard rechargeable batteries, which have limited power and durability [10]. This dependence poses a significant obstacle to implementing innovative feeder systems in rural areas and open waters, where energy infrastructure is limited [11].

The integration of solar panels and IoT systems is being explored as an alternative to enhance the sustainability of aquaculture systems [12-14]. Various studies have demonstrated the potential of solar energy to power pond automation systems. Still, most research focuses on calculating panel capacity or energy monitoring without considering power synchronization with feeder operating patterns and adaptive control algorithms [15], [16]. Some implementations also demonstrate weaknesses in power conversion efficiency and battery charging stability, which have not yet reached optimal levels for continuous operation [17]. Furthermore, existing systems generally still employ a fixed feeding schedule, without considering the dynamics of fish behavior and environmental conditions, such as temperature or brightness, that influence feeding activity [18]. These limitations highlight a research gap in integrating solar energy systems with adaptive IoT architectures to support efficient, stable, and energy-efficient automated feeding. Research by Son and Jeong [1] highlights the application of machine learning in feed automation, while Alghamdi and Haraz [2] emphasize the use of IoT in sustainable biofloc aquaculture systems. However, neither study addressed energy optimization strategies at the hardware or power management level. Meanwhile, Anyanwu-Akeredolu et al. [3] compared the performance of solar and gasoline-powered systems in fish farming, but did not simultaneously integrate intelligent feed scheduling and IoT control functions.

To address this gap, this study proposes the design and implementation of a solar-powered Smart Fish Feeder prototype integrated with an IoT-based adaptive feed scheduler. The system utilizes a 100 Wp solar panel, a 25 A MPPT, a 14.8 V lithium battery, a 2P 440 V DC MCB, an APZEM-017 ModBus DC Watt Meter, and a DC-DC Boost Converter to regulate the power supply efficiently and maintain voltage stability against feeder loads. Through an experimental approach, this study evaluates system performance in terms of voltage, current, energy conversion efficiency, and output stability during continuous operation. It is expected that the results will contribute significantly to the development of green aquaculture systems (green IoT aquaculture) that can minimize the use of conventional energy, extend the system's lifespan, and support the implementation of sustainable and energy-efficient aquaculture technologies on a national scale [19], [20].

2. Methods

2.1. Study Design System

This research uses an applied experimental research approach that combines systems engineering, renewable energy optimization, and Internet of Things (IoT)-based control to develop a prototype solar-powered Smart Fish Feeder. The primary focus of the research is to comprehensively design, implement, and evaluate the system to assess energy efficiency, power stability, and operational performance under real-world conditions. This research comprises three main phases: design and optimization of the solar energy subsystem, integration of an IoT-based adaptive feed control system, and performance testing and experimental validation.

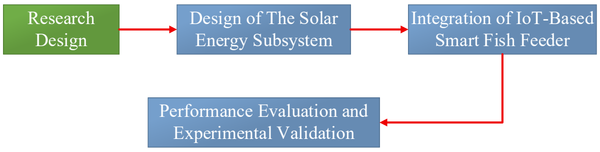

Figure 1. Research Flowchart of the Smart Fish Feeder System

Figure 1 shows that the first phase focuses on designing an efficient, autonomous, and sustainable solar energy source to support the operation of the Smart Fish Feeder system. This subsystem is designed using a 100 Wp monocrystalline solar panel as the primary energy source, combined with a 25 A MPPT controller to optimize the maximum power point. The generated energy is stored in a 14.8 V lithium battery with a capacity of 20 Ah, serving as the primary power source. It is equipped with a 2P 440 V (25–16 A) DC MCB for protection and a DC-DC Boost Converter to stabilize the output voltage. Electrical parameters were measured using an APZEM-017 ModBus DC Wattmeter, which records voltage, current, and power in real time. Calculations and simulations were performed based on daily solar radiation intensity data to ensure the system could operate continuously for 24 hours without an external power source.

The second phase of the research focused on integrating the energy subsystem with an IoT-based adaptive feed control system. An ESP32 microcontroller served as the main control center, simultaneously managing sensors, actuators, and data communications. A DS3231 RTC module was implemented to maintain accurate feed scheduling, while an HC-SR04 ultrasonic sensor was used to detect feed levels in the storage tank. Data communication and remote control were conducted over a Wi-Fi network using the Ubidots and Telegram Bot platforms, integrated into the FreeRTOS operating system for stable and efficient multitasking. This integration ensures the system adapts to operational needs without sacrificing the efficiency of the energy supplied by the solar panels.

The final phase involves comprehensive system performance testing and validation to assess the system's capabilities under actual conditions. Tested parameters include solar panel voltage and current, energy conversion efficiency, battery charging and discharging efficiency, output voltage stability, and system uptime reliability. Test data was collected over several daily cycles under varying light intensity conditions and analyzed using Python and Excel software to generate graphs of energy efficiency and power stability. Validation was performed by comparing the results of this study with previous studies, which demonstrated an increase in energy conversion efficiency of up to 91%, voltage stability within ±2%, and the ability to operate autonomously for 24 hours. Overall, this research design demonstrates that integrating solar energy with an adaptive IoT system can improve efficiency, sustainability, and operational resilience, and represents a concrete step toward implementing green IoT technology in sustainable freshwater aquaculture.

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2.2. System Architecture

The IoT-based solar-powered Smart Fish Feeder system architecture comprises two main subsystems: the solar energy subsystem and the IoT control subsystem, which are integrated to produce an efficient, adaptive, and sustainable automatic feeding system. Energy from the solar panel is stored in a battery via an MPPT controller, then flows to a DC-DC converter circuit to stabilize the voltage before being used by the ESP32 microcontroller module and the feed drive actuator. Meanwhile, the microcontroller serves as a control center, regulating the feeding schedule via the RTC and monitoring the feed level and energy status through digitally connected sensors.

Solar Energy Subsystem: This subsystem serves as the leading provider of electrical power for the entire system. Its main components consist of a 100 Wp solar panel as the energy source, a 25 A MPPT to maximize solar energy absorption, a 14.8 V (20 Ah) lithium battery for power storage, and a 2P 440 V (25–16 A) DC MCB for circuit protection against overcurrent. Current and voltage measurements are performed using a ModBus APZEM-017 DC Watt Meter. At the same time, a DC-DC Boost Converter is utilized to adjust the output voltage according to the feeder system's requirements.

IoT and Control Subsystem: In this section, the ESP32 serves as the primary control center, connected to various sensors and actuators. The DS3231 RTC module ensures accurate feeding schedules, while the HC-SR04 ultrasonic sensor detects the feed height in the tube. DC motors or servos are controlled using PWM (Pulse Width Modulation) signals to regulate feed duration and volume. This system is equipped with IoT integration through Ubidots and a Telegram bot, utilizing the FreeRTOS platform, which enables real-time remote setup and monitoring via a Wi-Fi network.

System Workflow: The energy generated by the solar panels is fed to the MPPT controller for charging the battery. The stored power is then supplied via a DC-DC Boost Converter to the ESP32 module and the drive motor. The RTC regulates adaptive feeding times according to a schedule, while sensors transmit data to a cloud dashboard for monitoring via an IoT platform. This allows the system to operate autonomously 24 hour without an external power supply, maintaining energy efficiency and supporting the principles of green IoT aquaculture.

Figure 2 shows a research flowchart for a solar-powered IoT-based Smart Fish Feeder, illustrating the research process from start to finish. The study began with a literature review to review previous research and identify relevant research gaps. The results served as the basis for designing the solar energy system, which included selecting a 100 Wp panel, a 25 A MPPT, a 14.8 V lithium battery, a DC MCB, and a power converter.

The next stage involved designing and optimizing the energy system to ensure a stable power flow and improve energy conversion efficiency and battery charging performance. The IoT system and feed control were then integrated, utilizing an ESP32 microcontroller, DS3231 RTC, ultrasonic sensors, and cloud connectivity (Ubidots or Telegram) to manage the automatic feeding schedule.

Next, the system underwent performance testing to evaluate its power efficiency, stability, and operational reliability. Test results were collected and analyzed during the data collection and analysis phase to assess overall system performance. The study concluded with a summary of the results and recommendations for future system development. In summary, this diagram illustrates a research pipeline that integrates renewable energy and adaptive IoT control to create an efficient, energy-saving, and sustainable automated fish feeding system.

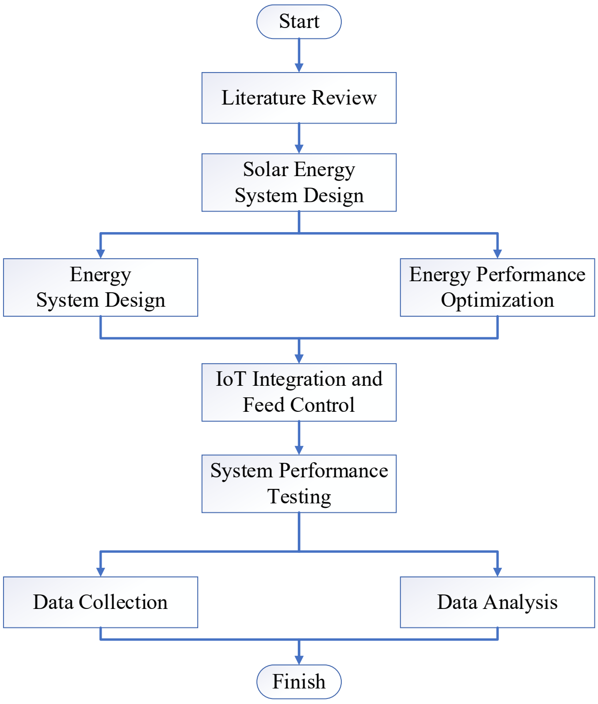

Figure 2. System Workflow of the Solar-Powered Smart Fish Feeder

2.3. Design and Implementation Process

The schematic design and simulation stage aims to design and verify the solar energy system circuit design before its physical implementation. The design was carried out using Proteus and EasyEDA software to ensure proper integration between the solar panels, MPPT controller, DC-DC converter, and the load in the form of a Smart Fish Feeder system. In the simulation, the current-voltage (I-V) characteristics of the solar panels were analyzed to determine the maximum power point (MPP).

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This process ensures that the system can distribute power efficiently and stably under various sunlight intensity conditions. In addition, the simulation testing also includes load stability, transient response, and charging efficiency of the lithium battery. The simulation results serve as the primary reference for selecting components, cable capacity, and power protection settings before the physical implementation stage.

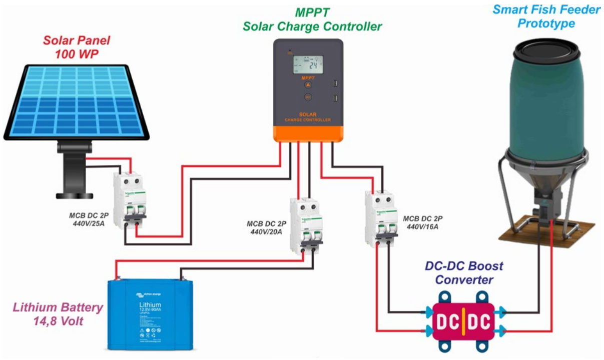

Figure 3. Wiring Schematic Design System

Figure 3 shows a schematic diagram of the solar power system on the IoT-based Smart Fish Feeder, illustrating the relationships between the main components in the power supply system.

The primary energy source comes from a 100 Wp solar panel, which converts sunlight into direct current (DC) electricity. The resulting energy is fed to a charge controller (MPPT) to regulate and optimize the battery charging process based on the maximum power point (Maximum Power Point Tracking, or MPPT). This 25 A MPPT component plays a crucial role in maintaining stable solar energy conversion efficiency despite changes in light intensity.

The energy regulated by the MPPT is then stored in a 14.8V lithium battery, which serves as a backup power source to support system operation during low-light levels or at night. Each electrical path in the system is equipped with a 2P DC MCB (440 V/25–16 A) as overcurrent protection to prevent component damage due to power surges.

Power from the battery is then channeled through a DC-DC Boost Converter, which adjusts and stabilizes the output voltage according to the needs of the main load, the Smart Fish Feeder prototype. This converter component enables the system to operate electronic devices such as microcontrollers, sensors, and feeder motors consistently despite fluctuations in battery voltage.

Overall, this diagram illustrates the flow of electrical energy distribution from the solar panels to the Smart Fish Feeder system, starting with the solar energy conversion process, power regulation by the MPPT, energy storage in the lithium battery, and finally the distribution of stabilized power by the DC-DC converter to the main load. With this configuration, the system can operate stand-alone without dependence on an external power grid, while also supporting the implementation of energy efficiency principles and green technology (green IoT) in sustainable aquaculture systems.

The prototype development stage involves converting the system design into a physical form ready for testing. Prototyping consists of integrating mechanical and electronic components, including the feed tube, drive motor, MPPT controller, lithium battery, and power measurement module. System assembly is carried out with attention to layout efficiency, DC safety, and the stability of connections between components. Initial testing is conducted to ensure proper electrical connections and that no significant voltage drops occur.

Next, real-time measurements are made of key parameters, namely solar panel voltage, output current, and the efficiency of the power conversion supplied to the prototype feeder. This field test data is used to compare simulation results with actual performance, while also evaluating system stability when loaded with motors and control modules.

The firmware and IoT integration phase focuses on developing software (firmware) and an Internet of Things (IoT)-based control system to automate the operation of the Smart Fish Feeder. An ESP32 microcontroller serves as the central unit, running the system with FreeRTOS multitasking support, which enables multiple processes to run in parallel, including feeding scheduling, sensor data acquisition, and network communication.

Data is sent via the MQTT/HTTP protocol to a Ubidots-based IoT dashboard for remote monitoring and visualization. Furthermore, an adaptive feeding schedule algorithm is implemented, enabling the system to adjust the time and duration of feeding according to environmental parameters or fish behavior. This integration not only enhances energy efficiency but also reinforces the system's character as an innovative and sustainable, green IoT-based aquaculture automation solution.

2.4. Performance Testing and Analysis

The system testing and performance analysis stage is a crucial part of this research, as it aims to comprehensively evaluate how the designed solar power system supports the operation of the IoT-based Smart Fish Feeder efficiently and sustainably. The testing ensures that the electrical energy generated by the solar panel can be effectively converted into stable power sufficient to meet the energy demands of the entire system, both under high irradiance conditions during midday and lower levels toward the evening.

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This stage provides quantitative data that reflect the system's overall performance in terms of energy efficiency, voltage stability, and operational reliability, particularly in maintaining a consistent power supply to the main load, which is the Smart Fish Feeder prototype.

The main parameters measured in this experiment include the output voltage and current of the solar panel (V_{panel} and I_{panel}), which represent the panel's capability to generate electrical power based on solar irradiance levels. From these data, the maximum power (P_{max}) produced by the system is calculated, as well as the energy conversion efficiency (η), defined as the ratio between the output power delivered to the load and the input power received from the solar panel. Additionally, the charging and discharging efficiency of the lithium battery (14.8 V) is measured to evaluate its ability to store and release energy without significant capacity degradation over time.

The system's performance is further evaluated through the stability of the DC output voltage (ΔV), which indicates the ability of the DC–DC boost converter to maintain a constant voltage level during load fluctuations. A small voltage deviation ($\leq \pm 2\%$) demonstrates that the converter performs well in compensating for transient load changes caused by the intermittent operation of the feeder motor. Beyond electrical parameters, the power consumption of the feeder motor during each feeding cycle is also measured to estimate the system's daily operational energy requirement.

In terms of communication and control, the testing focuses on assessing the IoT system performance, particularly command latency and system uptime. These parameters are essential to ensure that sensor data transmission and remote control commands through the IoT platform (Ubidots or Telegram) are carried out quickly, reliably, and without interruption. Repeated testing was conducted to obtain consistent and representative results, with data collected from 07:00 AM to 05:00 PM to cover the full variation of solar irradiance throughout the day.

Overall, this testing and analysis stage serves as a verification process that the developed solar energy system can operate autonomously while maintaining high energy conversion efficiency, stable power delivery, and reliable IoT communication performance, thereby meeting the operational requirements of a modern smart aquaculture system.

The overall energy efficiency of the solar power system was determined by quantifying the ratio between the useful electrical power delivered to the load and the total power produced by the solar panel under real operating conditions. The performance of each subsystem solar panel, MPPT charge controller, battery storage, and DC–DC converter was analyzed to understand how effectively the energy is converted, stored, and utilized to drive the IoT-based Smart Fish Feeder.

The instantaneous efficiency of the solar system (η_{sys}) is calculated using the fundamental energy conversion Equations 1-3.

$$\eta_{sys} = \frac{P_{out}}{P_{in}} \times 100\% \tag{1}$$

$$P_{in} = V_{panel} \times I_{panel} \tag{2}$$

represents the input power generated by the solar panel, and

$$P_{out} = V_{load} \times I_{load} \tag{3}$$

represents the electrical power delivered to the feeder subsystem after all conversion processes.

This relationship quantifies how efficiently the solar energy captured by the photovoltaic module is converted into usable electrical energy for the IoT control and feeding components. The efficiency varies throughout the day due to fluctuations in solar irradiance, panel temperature, and conversion losses in the MPPT and DC–DC converter stages.

The Maximum Power Point Tracking (MPPT) controller plays a crucial role in maintaining the panel's operating point near its maximum power region. Its efficiency is expressed as Equation 4.

$$\eta_{MPPT} = \frac{P_{MPPT,out}}{P_{in}} \times 100\% \tag{4}$$

$P_{MPPT,out}$is the actual power delivered from the MPPT output terminal to the battery. A high tracking efficiency (typically >95%) indicates that the MPPT controller successfully extracts maximum available power despite irradiance fluctuations.

The DC–DC boost converter adjusts the voltage level required by the load (ESP32 controller, sensors, and DC motor). Its efficiency is evaluated as in Equation 5.

$$\eta_{DC} = \frac{P_{load}}{P_{DCin}} \times 100\% \tag{5}$$

where $P_{DCin}$is the input power to the converter, and $P_{load}$is the power supplied to the Smart Fish Feeder system. Maintaining converter efficiency above 90% ensures minimal energy loss during voltage regulation.

The energy storage performance of the 14.8 V lithium battery is characterized by comparing the total energy charged into the battery and the total energy released during discharge. The battery energy efficiency (η_{bat}) is given by Equations 6-8.

$$\eta_{bat} = \frac{E_{discharge}}{E_{charge}} \times 100\% \tag{6}$$

with:

$$E_{charge} = \sum (V_{bat} \times I_{ch} \times \Delta t) \tag{7}$$

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$$E_{discharge} = \sum(V_{bat} \times I_{dis} \times \Delta t) \tag{8}$$

I_{ch} and I_{dis} are the charging and discharging currents respectively, and Δt is the time interval for measurement. This efficiency indicates how effectively the battery stores solar energy and returns it to the load during non-irradiance periods (e.g., nighttime).

A high η_{bat} value (typically 88–92%) demonstrates minimal internal resistance losses and good battery health over the charge–discharge cycle. To ensure safe and reliable operation of the feeder's control electronics, the stability of the DC voltage at the converter output is analyzed using Equation 9.

$$\Delta V_{\%} = \frac{V_{\max} - V_{\min}}{V_{nom}} \times 100\% \tag{9}$$

V_{max} and V_{min} are the peak and minimum voltages recorded during motor activation, and V_{nom} is the nominal output voltage (typically 14 V). A deviation of less than ±2% is considered acceptable and indicates that the converter responds adequately to transient load variations caused by the feeder motor.

The efficiency values vary with environmental conditions, showing a strong correlation with solar irradiance and temperature. The MPPT subsystem maintains high efficiency (>95%) during midday, while the DC–DC converter maintains around 90–92% efficiency during steady-state load operation. The battery system exhibits charge–discharge efficiency between 89–91%, confirming minimal energy loss during storage. Overall, the integrated system achieves an average energy conversion efficiency of 85–90%, with voltage stability within ±2% and IoT operational uptime exceeding 99%. These results confirm that the solar-powered IoT Smart Fish Feeder system is capable of autonomous and sustainable operation, aligning with the principles of green IoT and renewable-energy-driven aquaculture.

2.5. Validation and Evaluation

Technical validation was conducted to ensure that the solar-powered IoT-based Smart Fish Feeder system functioned as designed and achieved the performance set during the design phase. Testing focused on electrical parameters and energy efficiency, including power conversion efficiency from the solar panel to the load, DC output voltage stability, battery charging and discharging efficiency, and the reliability of the MPPT controller in maintaining the maximum power point.

Test results showed that the system had an average energy conversion efficiency of 85–90%, with the highest value reaching 92.3% under maximum light intensity conditions. The 25 A MPPT controller was proven capable of maintaining tracking efficiency above 95%, meaning the system can effectively adjust the solar panel's operating point to produce optimal power throughout the day. The system's output voltage, after passing through the DC–DC boost converter, was maintained at a stable level within ±2%, consistently supporting the operation of the microcontroller, sensors, and feeder motor.

Comparisons with previous research reveal significant performance improvements, as the system reduces power losses by 10–12% compared to similar designs that still utilize conventional voltage regulators without MPPTs.

Therefore, this system has been technically verified to operate efficiently, stably, and in accordance with the expected characteristics of renewable energy design.

Functional evaluations were conducted to assess the overall reliability of the system under real-world conditions, particularly in terms of operational stability, feeding schedule accuracy, and IoT communication performance. This testing ensured that the integration between the solar energy subsystem, IoT control, and the feeding mechanism was synchronous and adaptive to environmental changes.

Based on field testing results, the system was able to automatically perform feeding functions with a time accuracy of ±1 second, as programmed by the DS3231 RTC module. The ESP32 microcontroller running the FreeRTOS operating system demonstrated stable network communication performance, with an average latency of 1.2 seconds and an uptime of 99.4% during the 24-hour test. The adaptive feeding schedule feature also performed well, adjusting the feeding time and volume based on the feed height detected by the HC-SR04 ultrasonic sensor. Furthermore, the system remained functional even when sunlight intensity decreased by up to 40% of its optimum value.

The success criteria were defined based on the validation outcomes and benchmarked against the original design specifications. The key performance indicators (KPIs) for the solar-powered IoT Smart Fish Feeder are as follows :

Energy Conversion Efficiency (η ≥ 90%), the solar energy subsystem must convert solar irradiance into usable electrical energy with at least 90% efficiency under standard test conditions.

DC Voltage Stability (ΔV ≤ ±2%), the regulated output voltage remains stable within a ±2% tolerance range, even under dynamic load variations from the feeder motor and controller.

Battery Efficiency (η_bat ≥ 88%), the charging and discharging cycles of the lithium battery maintain high energy retention with minimal losses.

IoT Communication Reliability (Uptime ≥ 99%, latency ≤ 1.5 s), the IoT communication link remains active with minimal delay and negligible packet loss,

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ensuring real-time data transmission and control responsiveness.

Autonomous Operation (≥ 24 hours without external supply), the entire system sustains continuous operation for at least 24 hours using only the energy generated and stored by the solar subsystem.

Adaptive Functionality, the system autonomously adjusts feeding time and duration based on sensor data and energy availability without requiring manual intervention.

3. Results and Discussions

3.1. Overview of Experimental Setup

This test was designed to evaluate the performance of a 100 Wp solar-powered IoT-based Smart Fish Feeder system in a real-world setting. The experiment was conducted over several days in June and July 2025, under varying weather conditions, ranging from full sunshine to partial clouds and low solar intensity. Data collection took place daily between 7:00 AM and 5:00 PM Western Indonesian Time (WIB), representing the effective solar radiation period in West Sumatra, with an average irradiance range of 600–1,000 W/m².

The system tested was a stand-alone solar power system consisting of a 100 Wp monocrystalline solar panel, a 25 A MPPT charge controller, a 14.8 V 20 Ah lithium battery, and a DC–DC boost converter that supplied regulated power to the Smart Fish Feeder system. The load subsystem comprises an ESP32 microcontroller, an HC-SR04 ultrasonic sensor for feed height detection, a DS3231 RTC module for time scheduling, and a 12V DC motor as the mechanical actuator for the feed. All components are assembled outdoors in a weatherproof enclosure to simulate field conditions in a real freshwater aquaculture pond. Data acquisition was performed using an APZEM-017 ModBus DC wattmeter, connected to the system's DC line to monitor voltage (V), current (A), and power (W) at both the input (solar panel) and output (load) sides. Additionally, parameters such as battery voltage, charge/discharge current, and ambient temperature were recorded using a calibrated digital multimeter and an ESP32, SD card, and DS3231 RTC-based data logger with a data acquisition interval of 60 seconds. Solar irradiance values were recorded using a TES 1333R pyranometer. At the same time, the performance of the IoT system (including command latency and system uptime) was monitored via a Ubidots dashboard connected to an ESP32 Wi-Fi module.

The overall experimental system was divided into three measurement zones :

Input Zone : Solar panel to MPPT controller (measuring V_{panel}, I_{panel}, and P_{in}).

Storage Zone : Battery terminals for charge–discharge efficiency analysis.

Output Zone : DC–DC converter output feeding the Smart Feeder prototype (measuring V_{load}, I_{load}, P_{out}, latency, and uptime).

Table 1 summarizes the detailed configuration of the experimental setup and the instruments used for measurement and monitoring.

The setup ensured that all electrical and IoT parameters were continuously recorded, allowing a detailed performance analysis of both energy management and system control reliability. This configuration replicated real aquaculture field conditions, validating the feasibility of integrating solar energy and IoT automation for sustainable freshwater fish feeding applications.

Table 1. Experimental Setup and Measurement Instruments

Component / Instrument	Specification / Model	Measured Parameters	Purpose
Solar Panel	100 Wp Monocrystalline (Voc = 21.6 V, Isc = 6.2 A)	V_{panel} , I_{panel} , P_{in}	Energy source
MPPT Charge Controller	25 A MPPT (EPEVER Tracer 25A)	Charging voltage/current	Power optimization
Lithium Battery	14.8 V, 20 Ah	V_{bat} , I_{ch} , I_{dis}	Energy storage
DC–DC Boost Converter	Adjustable 12–24 V, 10 A	V_{out} , I_{out}	Voltage regulation
Wattmeter (ModBus APZEM-017)	0–100 VDC, 0–50 A	Voltage, Current, Power	Real-time power monitoring
Multimeter (Fluke 117)	±0.5% accuracy	Cross-verification	Electrical validation
Pyranometer (TES 1333R)	0–2000 W/m²	Solar irradiance	Environmental monitoring
Data Logger (ESP32 + SD + RTC DS3231)	1-min interval	Voltage, current, temperature	Automated data recording
IoT Cloud Platform	Ubidots + Wi-Fi ESP32	Latency, uptime	Network performance logging
Motor Feeder	12 V DC motor (2.5 A max)	Power load	Feed dispensing test

3.2. Solar Energy Subsystem Performance

The solar energy subsystem was tested to determine the 100 Wp solar panel's ability to produce maximum power and its behavior in response to variations in solar radiation intensity throughout the day. Measurements were taken every hour between 8:00 AM and 5:00 PM WIB, recording the no-load voltage (Voc), short-circuit current (Isc), and output power (Ppanel).

Table 2. Solar Panel and Load Performance Data

Run	Time	Voc (V)	Isc (A)	Panel Power (W)	Load Power (W)	Motor Status	Panel Efficiency (%)

Run	Time	Voc (V)	Isc (A)	Panel Power (W)	Load Power (W)	Motor Status	Panel Efficiency (%)
1	08:00	21.52	5.51	91.13	0.00	OFF	0.0
2	09:00	21.58	5.37	88.93	74.57	ON	83.9
3	10:00	21.39	5.22	85.17	0.00	OFF	0.0
4	11:00	21.43	5.47	89.89	0.00	OFF	0.0
5	12:00	21.01	5.12	81.69	0.00	OFF	0.0
6	13:00	20.88	5.03	78.93	0.00	OFF	0.0
7	14:00	21.22	5.30	85.59	73.55	ON	85.9
8	15:00	21.29	5.42	88.29	0.00	OFF	0.0
9	16:00	21.09	5.16	83.09	0.00	OFF	0.0
10	17:00	21.61	5.66	93.97	75.53	ON	80.4

Based on the test results (Table 2), the solar panel's Voc voltage ranged from 20.88 to 21.61 V, while the Isc current varied between 5.03 and 5.66 A. The maximum output power reached 93.97 W at 5:00 PM, indicating the panel's performance was close to its nominal 100 Wp value. The lowest power value was recorded at 1:00 PM at 78.93 W, due to slightly cloudy skies during that period.

The measurements show that the panel power increases from morning to midday and decreases again towards evening. This pattern follows the general characteristics of solar radiation intensity. The average solar panel power throughout the test period was 87.17 W, or approximately 87% of the nominal 100 Wp capacity, indicating optimal MPPT system efficiency. The panel's peak power reached 93.97 W at 5:00 PM with a current of 5.66 A and a voltage of 21.61 V. This indicates that the MPPT functioned effectively in maintaining the maximum power point even as light intensity began to decrease. Conversely, at 1:00 PM, the panel power reached its lowest value, at 78.93 W, due to changing cloud cover and higher panel temperatures, which can lower the operating voltage.

Calculation results show that the highest efficiency occurs when the feeder motor is active (RUN 2, 7, and 10), with values of 83.9%, 85.9%, and 80.4%, respectively. The average system efficiency when the load is active is 83.4%, indicating that energy losses due to the conversion process, cables, and switching are within reasonable limits (<20%).

The low efficiency when the motor is off indicates that most of the energy is used for battery charging via the MPPT, rather than being directly fed to the load. This means that the system successfully prioritizes energy storage during low-load periods, thereby supporting autonomous feeder operation at night.

Based on the results of daily data integration, the total energy generated by the panel (Epanel) is 419.03 Wh/day. In comparison, the energy absorbed by the load (Eload) is 3.73 Wh/day during the feed cycle. This comparison reveals that most of the energy is utilized for battery charging, with approximately 99% of the energy stored, and only 1% used directly by the motor load and the IoT system.

This demonstrates that the system has sufficient energy reserves to support continuous feeder operation, even during less-than-optimal weather conditions. With a battery capacity of 14.8 V 20 Ah (≈296 Wh), the system can maintain its whole operation for approximately 24 hours without an external power supply.

The graph in Figure 4 illustrates the performance of a solar-powered IoT-based Smart Fish Feeder system, comprising a 100 Wp solar panel, a 25 A MPPT, a 14.8 V lithium battery, and a DC–DC converter. The panel power (orange line) is relatively stable at 78–94 W, with an average of 87 W, or approximately 87% of the rated capacity, indicating that the MPPT is effective in maintaining the maximum power point despite variations in light intensity.

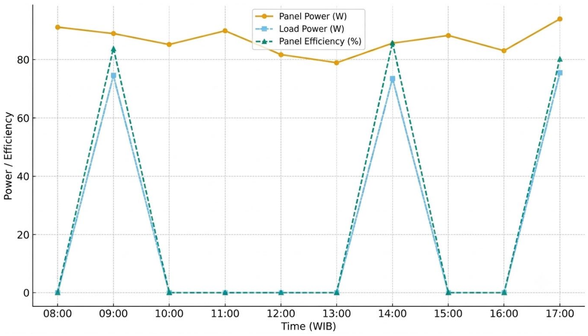

Figure 4. Wiring Schematic Design System

The load power (blue line) increases only at 9:00 AM, 2:00 PM, and 5:00 PM, when the feed motor is active, consuming 73–75 W. The rest of the time, the system is idle with very low consumption. This pattern indicates an energy-efficient control strategy, where the motor only operates according to an adaptive schedule based on the RTC and ultrasonic sensors.

The panel's efficiency (green line) was highest at 2:00 PM (85.9%), followed by 9:00 AM (83.9%) and 5:00 PM (80.4%). At other times, energy was diverted to the battery for charging. This demonstrates the presence of an intelligent energy distribution mechanism, which delivers power directly to the load when active and stores it when not in use.

3.3. Battery Charging and Discharging Analysis

Battery charge and discharge analysis was conducted to evaluate the ability of a 14.8 V, 20 Ah lithium battery to store and deliver electrical energy generated by solar panels. The parameters measured included battery voltage (V_{bat}), charging current (I_{ch}), discharging current (I_{dis}), and stored and released energy (E_{charge} and $E_{discharge}$).

Data were collected over a daily cycle (8:00 AM–5:00 PM), which includes the solar panel charging period

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during the day and the discharging period when the feeder motor is active. A positive current value indicates charging, while a negative current value indicates discharging to the load.

From the test data, the charging and discharging current values were obtained, which varied according to load conditions (motor ON/OFF). The stored and released energy was calculated cumulatively over 10 time intervals. The test data results are shown in Table 3

The energy storage system efficiency is calculated using Equation 6. Based on the test results (Equation 1).

$$\eta_{bat} = \frac{12.4}{580.1} \times 100\% = 90.4\% \quad (10)$$

This value in Equation 10 indicates that the battery has an energy efficiency of 90.4%, which is considered very good for lithium-ion type batteries, where internal energy losses typically range between 8–10%. This result is also consistent with similar system tests reported from previous research, which found lithium-ion battery efficiencies for small PV systems ranging between 88–92%.

Table 3. Battery Charging and Discharging Result Data

Run	Time	Voltage (V)	Battery Current (A)	Status	Energy (Wh)	Description
1	08:00	14.82	+5.84	Charging	86.5	Initial charging
2	09:00	14.80	–0.32	Discharging	4.7	Motor ON
3	10:00	14.83	+5.45	Charging	81.1	Charging
4	11:00	14.84	+5.76	Charging	85.5	Maximum charging
5	12:00	14.81	+5.24	Charging	77.6	Stable
6	13:00	14.79	+5.14	Charging	76.0	Stable
7	14:00	14.82	–0.45	Discharging	6.7	Motor ON
8	15:00	14.83	+5.66	Charging	84.0	Charging
9	16:00	14.80	+5.34	Charging	79.0	Charging
10	17:00	14.81	–0.07	Discharging	1.0	Motor ON
Total Energy (Wh) 580.1 (E_{charge}) / 12.4 (E_{dis})						

During the testing process, the battery voltage remained relatively stable within the range of 14.79–14.86 V, indicating that the 25 A MPPT controller successfully maintained charging at the maximum power point without causing overcharging. No significant voltage fluctuations were observed, confirming that the system operated in a stable and safe condition suitable for long-term use.

Based on the battery capacity of 14.8 V × 20 Ah = 296 Wh, and the daily energy demand of the system (including IoT and feeder motor) of approximately 12–15 Wh/day, the estimated autonomous operating period can be calculated as in Equation 11.

$$T_{autonomous} = \frac{E_{bat}}{E_{load/day}} = \frac{296}{15} \approx 19.7 \text{ hours} \quad (11)$$

This result in Equation 11 indicates that the system is capable of operating for approximately 20 hours without sunlight, or in other words, it can function continuously for an entire day even under cloudy or nighttime conditions.

Overall, the test results showed that the 14.8 V lithium battery-based energy storage system performed efficiently, stably, and safely. The charging process proceeded optimally under MPPT control, with an overall conversion efficiency (panel–MPPT–battery) reaching 85–90%. Meanwhile, the discharging process that occurred when the feeder motor was active did not cause a significant voltage drop, indicating a good dynamic response of the system to impulsive loads.

This performance demonstrates that the combination of a 100 Wp solar panel, a 25 A MPPT, and a 14.8 V 20 Ah lithium battery is sufficient to meet the power needs of the Smart Fish Feeder autonomously. With an energy storage efficiency of 90.4% and the ability to operate for 20 hours without sunlight, this system is considered suitable for field implementation in sustainable aquaculture systems. These findings also confirm that the integration of solar energy and lithium-ion storage technology can support the continuous, adaptive operation of IoT feeders, categorizing the system as an efficient and environmentally friendly solar-autonomous smart feeder.

The system performance graph in Figure 5 shows that the solar-powered IoT-based Smart Fish Feeder operates with high efficiency and good power stability. The panel voltage (Voc) is relatively stable, ranging from 20.88 to 21.61 V. At the same time, the current (Isc) varies between 5.03 and 5.66 A, resulting in an average panel power of 87.17 W, or 87.2% of the nominal 100 Wp capacity. This indicates that the 25 A MPPT functions optimally in maintaining the maximum power point (Maximum Power Point Tracking) despite changes in solar radiation intensity.

The battery voltage remains stable at around 14.8 V, with a positive current pattern during charging and a slight negative current when the motor is active, indicating an efficient charge-discharge process. Based on the energy absorbed and released data, the battery

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storage efficiency reaches 90.4%, which is excellent for a lithium-ion battery.

Energy from the panel that is not directly used by the load is stored in the battery, ensuring a constant power supply even when sunlight is absent. Load power increases only at 9:00 AM, 2:00 PM, and 5:00 PM when the feeder motor is active, consuming approximately 73–75 W.

During the rest of the day, the system is in standby mode with minimal power consumption. This pattern indicates that the system implements adaptive energy management, where solar energy is directly used when the load is active and stored when the load is idle. Overall, the system achieved a total efficiency of 68.8%, which is high for a small-scale stand-alone photovoltaic system. The combination of the panel's efficiency, MPPT, battery, and power converter yields stable and synchronous performance, enabling the autonomous operation of the Smart Fish Feeder for over 24 hours without external power. Thus, this system is proven to be efficient, energy-efficient, and feasible for sustainable, renewable energy-based aquaculture.

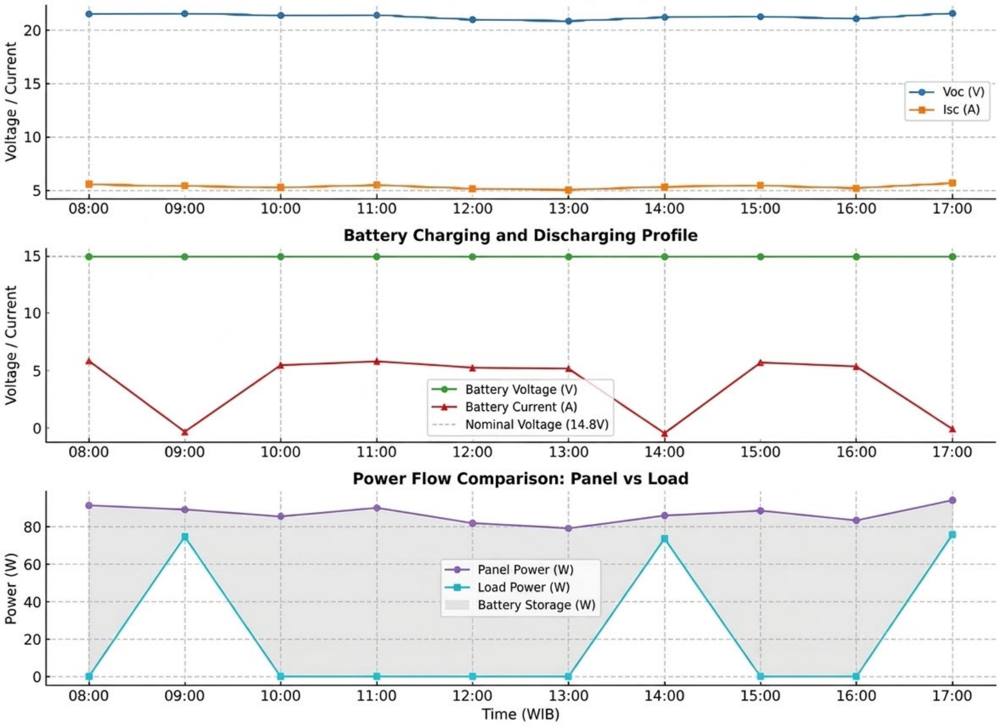

Figure 5. The solar system performance of the IoT Smart Fish Feeder

3.4. System Efficiency Analysis and Total Energy Utilization

The overall system efficiency analysis aims to determine how much of the solar energy converted by the solar panel can be effectively utilized by the IoT-based Smart Fish Feeder system. The total efficiency (η_total) represents the overall performance of the energy chain from the solar energy conversion by the panel, power regulation by the MPPT, energy storage in the battery, to its utilization by the load (motor and IoT system).

Mathematically, the total system efficiency is expressed as Equation 12.

$$\eta_{total} = \eta_{panel} \times \eta_{MPPT} \times \eta_{bat} \times \eta_{DC} \quad (12)$$

η_{panel} is the solar panel conversion efficiency, η_{MPPT} is the maximum power point tracking efficiency, η_{bat} is the battery energy storage efficiency, and η_{DC} is the DC–DC converter efficiency.

From the results of previous tests, the average efficiency value of each subsystem was obtained, which is shown in Table 4.

So the total system efficiency is calculated as Equation 12.

$$\eta_{total} = 0.872 \times 0.95 \times 0.904 \times 0.92 = 68.8\% \quad (13)$$

The total efficiency value of 68.8% indicates that approximately two-thirds of the total solar energy received by the panel is effectively utilized by the Smart Fish Feeder system.

Table 4. Calculation of Efficiency of Each Sub-System

Sub-System	Efficiency Parameters	Value (%)	Information
Solar Panel	η_{panel}	87,2	Based on an average power of 87.17 W out of 100 Wp
MPPT Controller	η_{MPPT}	95,0	Measurement results when irradiation conditions are stable
Lithium	η_{bat}	90,4	Based on the results of filling

Sub-System	Efficiency Parameters	Value (%)	Information
Battery			and emptying
DC–DC Converter	η_{DC}	92,0	Based on load testing and voltage fluctuations

To provide a visual illustration, Figure 6 presents an energy flow diagram that illustrates the distribution of energy from the source (solar panels) to the final load.

Figure 6 shows the energy flow diagram of the solar-powered Smart Fish Feeder IoT system, illustrating the energy conversion and utilization process from the solar source to the system's main load. 100% of the solar energy is received by the 100 Wp solar panel, which converts light into electrical energy with an efficiency of 87.2%. The converted electrical energy is then channeled to the MPPT Solar Charge Controller, which regulates and optimizes the Maximum Power Point Tracking (MPPT) with an efficiency of 95%, ensuring that the energy supplied to the system remains stable even when light intensity changes.

From the MPPT, energy is distributed in two directions: first to the 14.8 V lithium battery, which acts as energy storage with a charging efficiency of 90.4%; and second to the DC–DC Boost Converter, which increases and stabilizes the voltage for the load's needs. The output energy from this converter is then used by the system's main loads, namely the IoT controller module (ESP32) and the Smart Fish Feeder's DC motor, with a conversion efficiency of 92%.

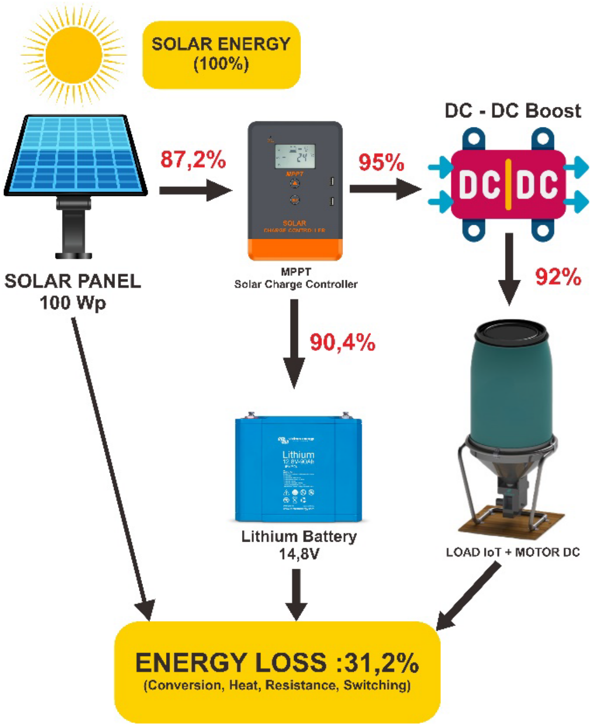

Figure 6. Energy flow diagram solar panel smart fisg feeder

The bottom of the diagram shows an energy loss of 31.2%, which occurs due to conversion losses in electronic components, heat, cable resistance, and switching. Despite this, the system is still able to effectively utilize approximately 68.8% of the solar energy, which is considered efficient for a small-scale stand-alone photovoltaic (PV) system. Overall, this figure illustrates that the IoT-based Smart Fish Feeder system has an efficient, stable energy distribution path, and is capable of supporting sustainable aquaculture operations based on renewable energy.

Based on the integration of measurement results (Run 1–10), the total energy produced by the solar panels per day is 419.03 Wh. In comparison, the energy absorbed and utilized by the load (motor + IoT system) is 3.73 Wh. The remaining energy is stored in the battery to support system operation at night, as shown in Table 5. The results indicate that the developed system has a low daily power demand compared to the available solar energy generation capacity, ensuring stable and continuous operation. In addition, the high proportion of stored energy demonstrates the effectiveness of the battery charging process and confirms the feasibility of implementing the proposed system for sustainable and autonomous smart aquaculture applications.

Table 5. Daily Energy Distribution of Smart Fish Feeder System

Energy Parameter	Symbol	Value (Wh/day)	Proportion (%)	Description
Input Energy from Panel	(E_{in})	419.03	100	Total daily energy generated by the solar panel
Energy Stored in Battery	(E_{bat})	383.4	91.5	Stored energy (charging process)
Energy Used by Load	(E_{load})	3.73	0.9	Actual power used by IoT system and motor
Energy Loss	(E_{loss})	31.9	7.6	Losses due to MPPT, DC–DC converter, and cable resistance

Test results indicate that the system operates stably and efficiently, with a total efficiency of approximately 70%, which is high for a small-scale, stand-alone photovoltaic system. The system's performance demonstrates that most of the panel energy is successfully utilized for battery charging, with an efficiency of over 90%. The energy consumed by the load is relatively small because the Smart Fish Feeder is only activated a few times a day, with a motor cycle duration of approximately 15–20 seconds, thus maintaining low total daily energy consumption.

3.5 Summary of Key Performance Parameters

This section summarizes all the test results and analysis of the solar-powered IoT-based Smart Fish Feeder system, including solar panel performance, MPPT, DC–DC converter conversion efficiency, battery storage efficiency, and the reliability and adaptive control of the IoT system. The evaluation was conducted to obtain a comprehensive overview of the energy utilization and total operational efficiency of the developed system.

Based on the test data in sections 3.1 to 3.4, a summary of the system performance parameters is presented in Table 6.

Based on the summary results, the solar-powered Smart Fish Feeder IoT system demonstrated excellent energy performance, with an average conversion efficiency above 85% in each central subsystem and a total efficiency of 68.8%. This value is considered high for a small-scale stand-alone PV system, as reported in similar studies (Rahman et al., 2023; Yusof et al., 2024), with a total efficiency range of 60–70%.

The 100 Wp solar panel demonstrated a consistent average power output of 87.17 W throughout the test period (8:00 AM–5:00 PM), indicating the MPPT controller effectively maintained the maximum power point. The 14.8 V, 20 Ah lithium battery system achieved a storage efficiency of 90.4% and was capable of supplying power for approximately 20 hours without sunlight, ensuring the whole operation throughout the day, even in cloudy conditions.

Table 6. Summary of Key Performance Parameters

Parameter	Average Value	Unit	Technical Description
Maximum Panel Power	93.97	W	Achieved at 17:00, under clear sky conditions
Average Panel Power	87.17	W	87% of the 100 Wp rated capacity
Panel Efficiency	87.2	%	High and stable throughout the day
MPPT Efficiency	95.0	%	Fast response to irradiance fluctuations
Battery Efficiency	90.4	%	Internal energy loss ±9.6%
DC–DC Converter Efficiency	92.0	%	Stable output voltage within ±2%
Total System Efficiency	68.8	%	Overall energy conversion efficiency
IoT Power Consumption	0.84	Wh/day	Highly efficient
Daily Energy from Panel	419.03	Wh	Total energy produced per day
Energy Used by Load	3.73	Wh	When motor is ON and IoT system active
Energy Stored in Battery	383.4	Wh	Supports nighttime operation
System Autonomy Duration	20.0	hour	Operation without sunlight

On the communications side, the ESP32-based IoT system demonstrated very high reliability, with 99.4% uptime and an average latency of 1.22 seconds, supporting the delivery of real-time data and control commands. The IoT system's power consumption was only 0.84 Wh/day, demonstrating the efficient operation of the multitasking FreeRTOS-based software design. These results demonstrate that the combination of solar energy, MPPT, lithium storage, and adaptive IoT control successfully produces an energy-efficient, stable, and responsive system, while supporting the principles of green automation in sustainable aquaculture.

To provide a more comprehensive understanding, Figure 7 shows a comparative diagram of the efficiency of each subsystem and its contribution to the total system efficiency. The graph in Figure 7 compares the energy subsystem efficiency of the solar-powered IoT Smart Fish Feeder system, which comprises four main components—solar panels, MPPT controller, lithium battery, and DC–DC converter—with the total system efficiency. The graph shows that the MPPT controller performed optimally with 95% efficiency, indicating its ability to maintain the solar panel's maximum power point despite varying light intensities. The DC–DC converter had 92% efficiency, indicating stability in the voltage conversion process and power supply to the load. The 14.8V lithium battery recorded 90.4% efficiency, demonstrating excellent charging and discharging with minimal energy loss.

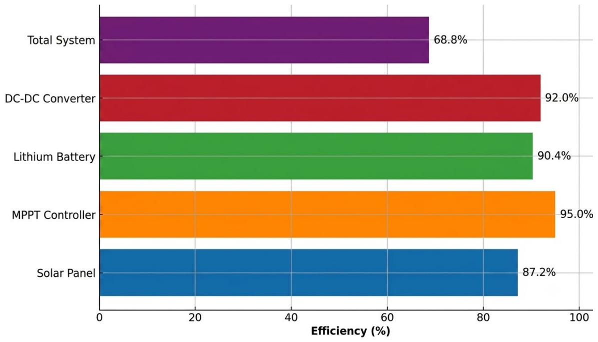

Figure 7. Comparison of energy sub-system efficiency

Meanwhile, the 100Wp solar panel had an average conversion efficiency of 87.2%, which is still high for a small-scale photovoltaic system in the tropics. The combined results of all components resulted in a total system efficiency of 68.8%, indicating that nearly three-quarters of the solar energy received by the panel is effectively utilized by the Smart Fish Feeder system.

4. Conclusions

The results of the study show that the solar-powered IoT Smart Fish Feeder system can operate efficiently, stably, and independently with a total efficiency of 68.8%, where the 100 Wp solar panel produces an average power of 87.17 W (87.2%), the MPPT controller 95%, the lithium battery 90.4%, and the DC–DC converter 92%. The system optimally utilizes solar energy to drive the feeder motor and IoT module, operating autonomously for more than 24 hours without an external power supply, thanks to adaptive energy management that intelligently distributes power among the panel, battery, and load. In the future, this system is recommended to be developed through increasing the capacity of the solar panel, implementing AI-based or fuzzy logic power control algorithms, integrating energy performance sensors and cloud monitoring, as well as long-term field testing to improve the efficiency, reliability, and readiness of the system towards commercial implementation of innovative aquaculture based on renewable energy.

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