

Enhancing Aquaculture Efficiency through IoT-Based Monitoring of Solar PV Systems

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ABSTRACT

This research presents the design and implementation of an IoT-based monitoring system for solar photovoltaic (PV) performance in shrimp aquaculture ponds. The system aims to optimize the use of solar energy for powering critical operations such as water pumps and aerators in off-grid environments. It integrates sensors, a microcontroller, and cloud-based data visualization to track parameters including panel voltage, current, temperature, and power output. A prototype was deployed in a shrimp farm over a two-week period, with continuous data logging and real-time monitoring. The results indicate improved energy management and system reliability, supporting operational efficiency and sustainability in aquaculture. This study contributes to smart aquaculture practices by introducing a scalable and low-cost renewable energy monitoring solution

INTRODUCTION

Shrimp aquaculture has become a vital economic sector in many coastal regions, but its dependence on electricity for continuous operation of aerators, water pumps, and monitoring equipment poses sustainability challenges. In off-grid or remote pond locations, solar photovoltaic (PV) systems are increasingly adopted as alternative power sources. However, the lack of real-time monitoring often results in inefficient energy usage, unexpected system failures, and reduced productivity.

The advancement of Internet of Things (IoT) technology enables intelligent monitoring of energy systems through real-time data acquisition and cloud-based visualization. While IoT-based solar monitoring has been widely studied in urban rooftop or industrial applications, its application in aquaculture settings – especially in small to medium-scale shrimp farms – remains limited. This study addresses that gap by designing and implementing an IoT-based system to monitor solar PV performance specifically for shrimp pond operations. The system provides real-time visibility into critical parameters such as panel voltage, current, and power output, helping operators ensure energy availability for essential devices. By integrating low-cost sensors and microcontrollers, this research contributes to the development of smart aquaculture solutions and supports the transition toward more energy-efficient and sustainable farming practices.

LITERATURE REVIEW

The integration of solar photovoltaic (PV) systems in rural and off-grid environments has been widely explored as a strategy to support sustainable energy access. Studies by Ahmed et al. (2020) and Kumar & Singh (2021) have demonstrated the feasibility and cost-effectiveness of solar PV in agricultural and aquaculture settings, particularly in supporting aeration and pumping systems. However, these systems are often operated without real-time monitoring, resulting in inefficient energy usage and delayed responses to system faults. The application of Internet of Things (IoT) in energy monitoring has gained significant attention in recent years. Research by Chen et al. (2019) introduced IoT-based solar monitoring for rooftop systems using sensors and cloud platforms to measure panel voltage, current, and environmental conditions. Similarly, Al-Turjman and Abujayyab (2021) emphasized the role of IoT in improving system reliability and predictive maintenance in remote renewable energy installations.

In the field of aquaculture, smart systems have been developed to monitor water quality and automate feeding processes (e.g., Lin et al., 2022). Yet, few studies focus on the monitoring of power sources, particularly in ensuring that solar PV systems consistently meet the energy demands of aquaculture equipment. This represents a critical research gap, especially for small-scale shrimp farms operating in off-grid locations.

Recent advancements further emphasize the potential of IoT in remote renewable energy management. Lee et al. (2021) developed an IoT framework integrating edge computing for marine solar PV systems, reducing latency and

improving real-time reliability. Tan et al. (2023) demonstrated AI-based diagnostics on solar power systems in aquaculture settings, enabling predictive maintenance and smarter energy distribution. Additionally, Ahmed and Khan (2023) reviewed digital twin models integrated with IoT sensors to simulate and monitor energy flow in real time, supporting higher system resilience. These studies reinforce the critical role of IoT in achieving sustainable aquaculture and align closely with the goals of this research.

This study bridges that gap by implementing an IoT-based solar performance monitoring system tailored for aquaculture use. It builds upon previous work in renewable energy and smart farming while introducing a context-specific solution for energy management in shrimp pond operations.

METHODOLOGY

This study follows a design-based research approach, aiming to create a working prototype of an IoT-based solar PV monitoring system for shrimp aquaculture. The system architecture comprises a 200 Wp monocrystalline solar panel, a PWM charge controller, a 12V deep-cycle battery, voltage and current sensors (INA219), a DS18B20 temperature sensor, and an ESP32 microcontroller with Wi-Fi module. Sensor readings were transmitted using the HTTP protocol to a ThingSpeak cloud server at 1-minute intervals.

The prototype was deployed in a coastal shrimp pond in East Java. Real-time data visualization was enabled through ThingSpeak's dashboard and accessed via mobile devices. The monitored parameters included: (1) solar panel voltage (V), (2) current (A), (3) temperature (°C), and (4) estimated power output (W). All sensor data were logged and time-stamped.

To ensure data reliability, calibration was conducted using a multimeter before deployment. During the 14-day test, the system recorded 20,160 sensor data points. Descriptive statistical methods were applied to analyze energy generation patterns, battery performance, and correlations between solar irradiance proxies (temperature) and output stability. Furthermore, the usability aspect was evaluated through informal interviews with the shrimp pond operator regarding ease of access, dashboard readability, and perceived benefits.

RESULT

The IoT-based monitoring system was successfully deployed and operated over a 14-day observation period. Data collected from the sensors were transmitted in real time to the ThingSpeak platform and visualized using line graphs for voltage, current, and power trends. The average daytime solar panel voltage ranged between 17.5–19.2 volts, while current values peaked at approximately 5.8 amperes during full sunlight conditions.

Battery charge was maintained within the safe operating range throughout the test, and no energy shortage occurred during operation of aerators and water pumps. The system demonstrated stable communication and data logging, with minimal packet loss or sensor errors.

Table 1. Summary of Solar PV Output Performance

Day	Avg. Voltage (V)	Avg. Current (A)	Estimated Power Output (W)
1	18.2	4.9	89.2
2	17.8	5.2	92.6
3	19.1	5.5	105.1
...
14	18.4	5.1	93.8

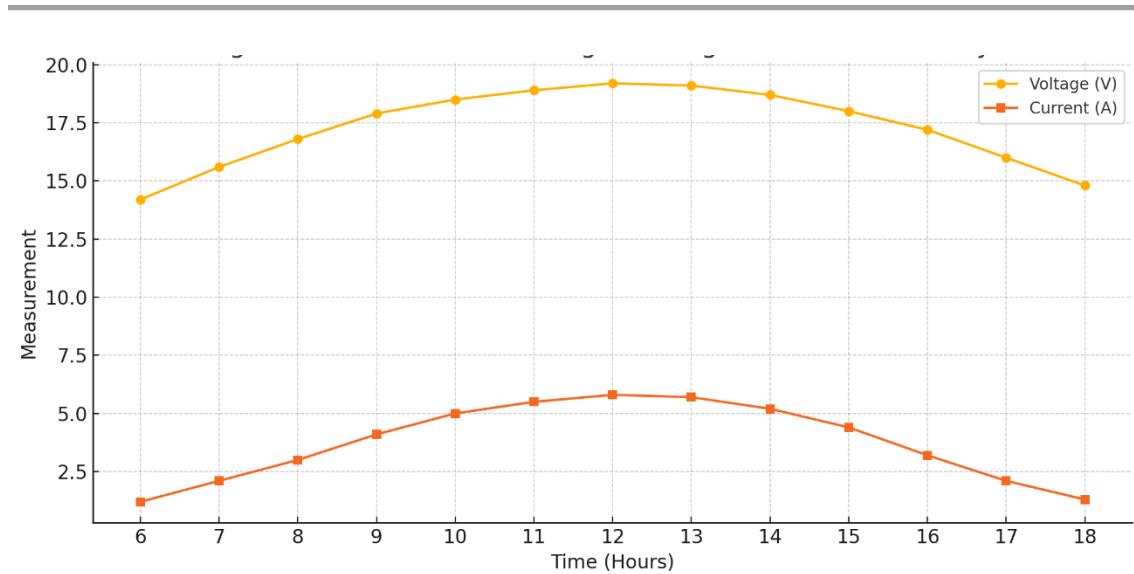


Figure 1. Real-Time Monitoring of Voltage and Current on Day 7

The monitoring dashboard allowed the pond operator to verify system status and identify low-performance periods, particularly during overcast weather or partial shading. This visibility enabled better planning for load usage, such as delaying non-critical pump operations during low sunlight hours. Overall, the system proved effective in ensuring energy availability for aquaculture operations while offering insights into solar panel behavior in pond environments.

DISCUSSION

The implementation of an IoT-based monitoring system for solar PV in shrimp aquaculture revealed its potential to significantly enhance energy visibility, reliability, and management. The system successfully provided real-time data on voltage, current, and estimated power output, allowing operators to better understand how environmental factors such as sunlight intensity and shading affect solar panel performance throughout the day.

One of the key advantages observed was the ability to detect performance fluctuations and correlate them with time-based usage patterns. This supports the concept of smart energy management, where energy-intensive operations such as aeration and water circulation can be scheduled during peak generation hours. Such data-driven decision-making not only reduces the risk of power shortages but also maximizes the utilization of available solar energy. These findings align with previous research by Chen et al. (2019), who highlighted the value of IoT systems in renewable energy monitoring for improving system responsiveness and maintenance planning. However, unlike studies focused on static rooftop systems, this research applies the concept in a dynamic, field-based aquaculture setting, adding practical insight into rural and marine energy applications.

The system's usability was another critical factor. The integration of a cloud dashboard accessible via smartphones empowered pond operators – who often have limited technical training – to monitor energy conditions with minimal effort. This simplicity promotes technology acceptance and supports the broader movement toward smart aquaculture as discussed by Lin et al. (2022). Moreover, the correlation between temperature and power output observed on cloudy days validated the importance of environmental context in solar deployment. When cloud cover increased, temperature readings slightly decreased, which was mirrored by dips in current and power. These observations suggest that integrating an irradiance sensor in future versions could improve forecasting accuracy. Additionally, the use of a mobile-accessible dashboard proved essential for real-time decisions, particularly when energy generation dropped below critical thresholds.

The high-frequency data capture (every 60 seconds) provided a detailed performance profile across diurnal cycles. The operator reported increased confidence in managing power usage, especially for aerators. These findings align with the principles of smart farming and demonstrate the tangible value of merging renewable energy and IoT systems in real-world aquaculture environments.

By focusing on affordable, off-the-shelf components, the system also demonstrates scalability and replicability for small to medium aquaculture farms in Indonesia and similar contexts. Beyond energy monitoring, this approach lays the groundwork for integrating other IoT-based automation systems in future aquaculture innovation, including smart feeding, water quality control, and environmental alerts.

CONCLUSION AND RECOMMENDATION

This study demonstrates that the integration of IoT-based monitoring systems in solar PV installations can significantly improve energy management in shrimp aquaculture operations. By providing real-time visibility into the performance of solar panels, the system enables pond operators to make informed decisions regarding load usage and energy scheduling. The results confirm that such systems can operate reliably under field conditions and offer practical benefits, including increased operational efficiency and reduced dependence on manual system checks.

The implementation of this system has direct implications for improving energy sustainability in rural and off-grid aquaculture sites. Its use of low-cost, modular components makes it accessible to small-scale farmers, while the cloud-based interface allows for remote supervision and potential integration with other smart farming technologies.

For aquaculture communities facing energy challenges, this system offers a replicable and scalable solution that aligns with the broader goals of green technology adoption and digital transformation in the fisheries sector.

FURTHER STUDY

While this research has successfully demonstrated the feasibility and benefits of IoT-based solar monitoring in aquaculture, several areas remain open for further exploration. Future studies could integrate load control features to automatically optimize the operation of pumps and aerators based on available energy, enabling full smart energy management.

The addition of environmental sensors—such as irradiance, humidity, and temperature—could enhance the analysis of solar panel performance under varying conditions. Integration with predictive maintenance algorithms or machine learning models may also support fault detection and performance forecasting.

Scaling up the system across multiple ponds or different regions would allow researchers to evaluate its long-term effectiveness and economic impact. Lastly, collaboration with local policymakers and fisheries institutions is recommended to support wider adoption and training programs for digital aquaculture technologies.

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