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Hybrid Solar and Wind Energy Integration for Smart Electric Fence Systems

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Abstract

Reliable protection off grid has become more important when farmers need to protect their crops for extended periods without being fully reliant on grid electricity, and electric fence systems have become more popular. The study proposed the design of IoT based hybrid solar wind energy system for smart electric fence system in the banana farm environment and tested the performance of the proposed system. The key contribution of this work is the implementation of two renewable energy sources with real-time voltage monitoring platform using ESP32 and Blynk, along with battery storage. The prototype was made up of a solar panel, wind turbine, charge controller, 12 V gel battery, energizer, aluminium fence conductor and IoT monitoring unit. To carry out experimental testing, voltage, current and power output were measured for wind turbine, solar panel and hybrid (wind and solar) system separately. The wind turbine generated 4.92-8.37 W, the solar panel generated 7.61-26.77 W and the combined hybrid system generated 21.97-27.80 W. The hybrid configuration provided the best operating voltage stability of 12.35-12.93 V and maximum output of 27.80 W. The ESP32-Blynk subsystems were able to display the battery voltage in real-time and alert the user when the voltage is above the threshold. The results suggest that solar and wind powered smart electric fence systems with IoT monitoring could be more reliable and useful for agricultural security applications in the remote areas.

1. Introduction

Rural and semi-remote agricultural regions are at risk of animals intruding and accidental encroachment and theft in banana farms. Traditional fencing options like barbed wire and wooden fences offer passive protection and can be costly to maintain. Electric fencing is more effective as it provides a controlled electric pulse on the fence line; however it requires the fence to be continuously powered and installed correctly.

Many farms are in rural areas where access to a main power grid is difficult or expensive. So, renewable energy is an appropriate solution for providing power to low-power agricultural security systems. Solar PVs work when the sun shines, and small wind turbines can supply extra energy when there is wind. Hybrid solar-wind systems can minimize the reliance on one energy source and enhance the availability of power in off-grid settings. Previous research also indicates that IoT can assist with real-time data collection and monitoring of distributed energy systems (Al-Fuqaha et al., 2015; Gubbi et al., 2013).

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Hence, the primary research gap to be filled in this study is limited practical testing of smart electric fence which incorporates stable fence construction, hybrid renewable energy generation and IoT based voltage monitoring in a single integrated smart electric fence prototype. Current agricultural fence solutions are mostly mechanical fencing, electric fencing or remote monitoring individually. But, not many papers cite the performance of a solar-wind power source along with the real-time battery voltage monitoring in a farm-scale electric fence. The gap is significant, as it is crucial that off-grid farms have a system that is not only mechanically strong, but can also ensure the power remains available and alert them to any abnormal situations in the power supply.

The novelty of this work is the use of three components in a practical way, which are a structure of a 5-line smart electric fence, a hybrid charging system of solar and wind power for a 12 V gel battery and an ESP32-Blynk monitoring unit. The proposed system has two renewable energy inputs, which increases the system's power stability and enables real-time voltage supervision which decreases the necessity for frequent manual inspection, compared with a conventional electric fence which relies on a single battery or solar energy input. The specific objective is to build an electric fenced with suitable wire-straining technique, to design an IoT-enabled hybrid renewable power system and to assess the performance of the hybrid system for the powering of a smart electric fence for agricultural protection.

2. Methodology

This study adopted an experimental prototype development approach. The work was conducted in four main stages: requirement identification, system configuration, fence construction and performance testing. The requirement identification stage considered the agricultural environment, expected animal intrusion, fence continuity, battery voltage level and remote monitoring needs. The system configuration stage selected the renewable energy components, battery storage, energizer and IoT monitoring unit. The construction stage focused on installing the electric fence structure and maintaining wire tension. The testing stage measured the power output of the wind turbine, solar panel and combined hybrid system, followed by verification of the ESP32-Blynk voltage monitoring function.

2.2 System configuration

The proposed system consists of two main subsystems: a renewable energy subsystem and an IoT monitoring subsystem. The renewable energy subsystem uses a solar panel and wind turbine to charge a 12 V gel battery through the relevant charge controllers. The stored energy supplies the electric fence energizer. The IoT subsystem uses an ESP32 microcontroller, a voltage sensor and the Blynk platform to monitor battery voltage remotely and provide alert notification when the voltage exceeds the defined threshold.

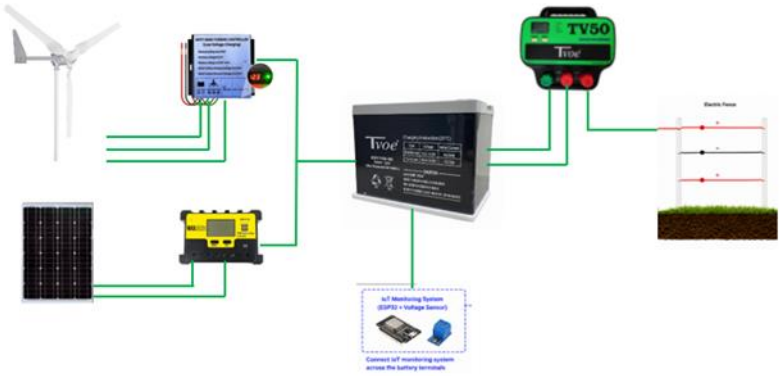


Figure 1: Hybrid Component Integration

Table 1 Main components used in the developed smart electric fence system

Component	Model/Type	Key specification
Solar panel	Maxson FNEF105-50	50 W, 18 V, 540 mm x 510 mm x 17 mm
Wind turbine	Three-blade turbine	300 W, 12 V, 538 mm blade length, 2.0 m/s starting wind speed
Solar charge controller	Maxson PWM controller	12/24 V compatibility, USB 10 A output
Wind turbine controller	MPPT controller	8 V start-up for 12 V system, 600/800 W rated controller power
Battery	Maxson EBY 108-55 gel battery	12 V, 55 Ah storage capacity
Fence conductor	Aluminium wire	2.0 mm single-strand conductor for electric fence application
IoT unit	ESP32, voltage sensor and Blynk	Wi-Fi communication, 0-25 V sensor input, mobile dashboard and alert

2.3 Electric fence construction

The smart electric fence was set up for a banana plantation. A 100 m long tested section of fence was erected using C-channel posts, PVC pipe posts, two-hole, medium-duty insulators, and insulators and wire tighteners. The C-channel posts were spaced at around 15 m and the PVC pipe supports at around 1.3 m to increase wire stability. 5 lines of aluminium wire were set to make contact with the target species like wild boar, monkeys and stray livestock. The wire was tightened in stages with tighteners and sagging was checked by uniformity of the wire throughout the section of the fence.

2.4 IoT monitoring and experimental testing

The ESP32 was programmed to read the analogue signal from the voltage sensor, convert it into an estimated voltage value and send the reading to the Blynk dashboard. Virtual pins were used to display voltage, set the voltage threshold and control the buzzer mute function. The alarm was configured to activate when the voltage exceeded 14 V, and the alert could be monitored through the Blynk mobile application. Experimental testing was conducted for the wind turbine, solar panel and combined hybrid system by recording voltage, current and rotational speed where applicable. Power output was calculated using $P = V \times I$, where P is the generated power in watts, V is voltage and I is current.

The experimental data were recorded as time-based measurements for each operating source rather than as controlled repeated trials under identical wind speed and solar irradiance conditions. For this reason, the reported results are presented as measured ranges and maximum observed outputs instead of averaged replicate values with standard deviation. This limitation is important because renewable energy output naturally fluctuates with weather, light intensity and wind speed. Nevertheless, the recorded ranges are useful for comparing the relative behaviour of the wind turbine, solar panel and combined hybrid system under actual farm testing conditions. Future work should repeat each test condition at least three to five times under controlled load and environmental conditions so that mean values, standard deviation and error bars can be reported.

3. Results and Discussion

3.1 Electric fence installation

The constructed fence demonstrated a stable layout with consistent wire positioning. The use of insulators reduced current leakage through the support structure, while tighteners helped maintain wire tension. The implemented materials included 280 PVC pipes, 30 C-channel posts, 2194 m of aluminium wire, 30 standard insulators, 100 two-hole insulators and 30 tighteners. These components provided the mechanical structure required to support the electric fence and maintain electrical continuity across the tested section.

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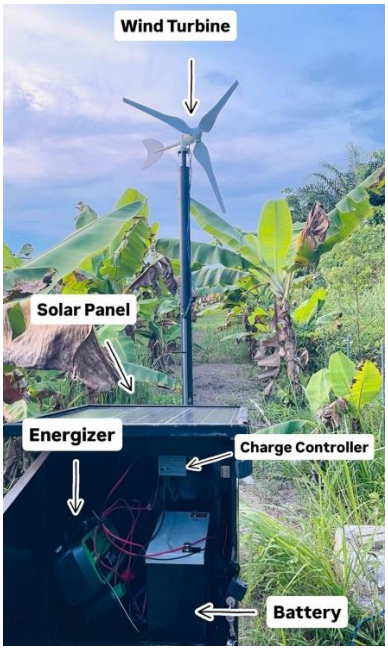


Figure 2: Hybrid Solar and Wind Turbine Integration

Table 2 Summary of experimental power output for individual and hybrid sources

Source	Voltage range (V)	Current range (A)	Power range (W)	Maximum output
Wind turbine	2.32-4.43	1.75-2.12	4.92-8.37	8.37 W at 20:35
Solar panel	4.12-12.93	1.75-2.07	7.61-26.77	26.77 W at 17:40
Hybrid solar-wind system	12.35-12.93	1.77-2.15	21.97-27.80	27.80 W at 17:35

During the test period, the wind turbine produced a power between 4.92 W and 8.37 W. The results showed that the higher the rotational speed the higher the voltage and power produced by the turbine, with the highest turbine output at 388.1 rpm. This behaviour is consistent with the operating principle of small wind turbines, where the wind speed and rotor speed affects the generator output (Islam et al., 2013).

The wider solar power range of 7.61 W to 26.77 W was found during good solar irradiance, whereas during the evening the solar output was lower with lower solar irradiance. The solar source was thus a major contributor when operating during the day, but was less dominant when the sun intensity was lowered.

The output of the combined hybrid system remained stable with a voltage of 21.97 W to 27.80 W, which is different from the individual systems. This result indicates that the solar panel and wind turbine were complementary, and enhanced the stability of the power supply. This stability is necessary when using electric fencing as the energizer and monitoring unit can only provide farm security if they are continually powered.

There is also a comparison of the output ranges that explains the results observed. The range of output of the wind turbine was 3.45 W and that of the solar panel was 19.16 W. This broad solar variation was due to the fact that the output of the solar panel is significantly influenced by the amount of solar radiation and time of measurement. The highest output level was achieved in the hybrid system, which differed by 5.83 W. This means that the weakness of the reliance on just one renewable energy source was reduced in the hybrid source. If the energy output from the wind turbine was reduced, it still supplied extra energy, and if the energy output from the wind turbine was limited, the energy output from the solar panel was still more.

This study provides an added dimension to previous studies on electric fences which were predominantly concerned with either the voltage of the fence or the type of conducting wire or animal-exclusion efficacy, and introduces a practical approach to renewable energy and monitoring of the fence by showing how a smart electric fence can be remotely powered and supervised. The current prototype is an application of the concept of monitoring directly in a farm security system where the battery voltage is displayed in real-time and an alert is sent by Blynk using the ESP32. Thus, the benefit of the proposed system is utilization of renewable energy not only but also, the ability to remotely view the power condition prior to the fence becoming ineffective.

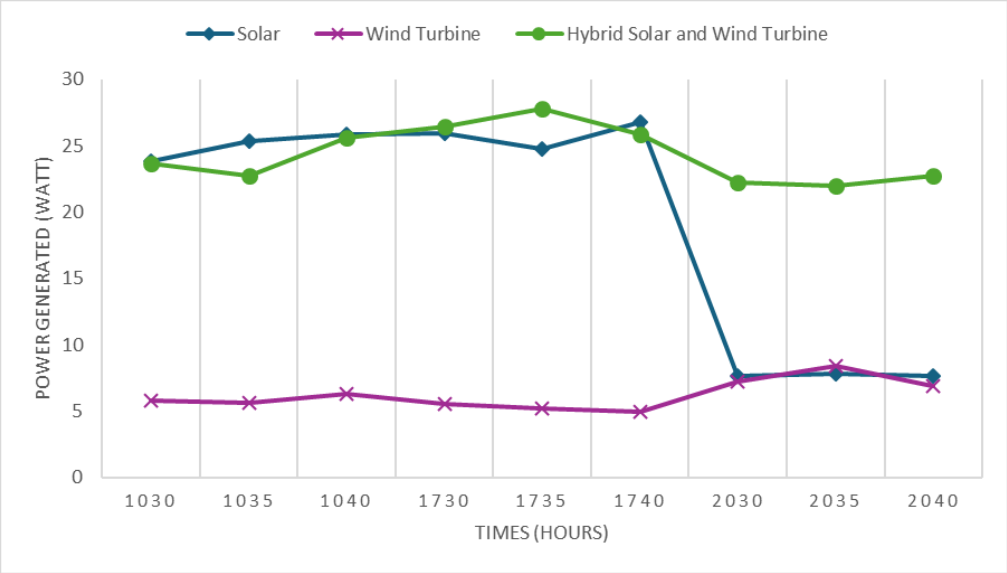


Figure 3: Power Generated By Solar, Wind Turbine And Hybrid

3.2 IoT monitoring performance

The ESP32 and Blynk monitoring system successfully displayed the measured voltage in real time. The dashboard allowed the user to monitor the system remotely and to respond when the voltage moved beyond the specified operating limit. The buzzer and notification functions provided an additional alert mechanism for abnormal voltage conditions. This confirms that the IoT subsystem can improve operational awareness and reduce the need for physical inspection at the farm site.



Figure 4: Monitoring Blynk

A practical aspect, the proposed system is able to be installed in semi-remote areas and rural farms because it helps to minimize dependence on the grid, and enables users to check on battery status with a mobile application. Hybrid energy source is also more power continuous than a single source. The study has a number of limitations, however. Testing was done within a restricted time frame, and was not designed to test long-term durability, animal-contact response, or long-term weather exposure. The system was also not tested with various electrical load profiles for prolonged durations. Future studies should focus on these limitations, with longer field trials, more repeated tests, and data logging and testing actual intrusion events to evaluate system performance.

4. Conclusion

A smart electric fence system powered by solar and wind energy using IoT for agricultural protection was successfully developed and evaluated in this study. The project focused on the requirement to build a viable off-grid fencing solution that does not require expensive installation work and can offer materials, renewable power supply and real-time monitoring in one prototype. The electric fence was made with aluminium wire, PVC supports, C channel posts, insulators and tighteners to ensure stability of the wire and electrical continuity. The five wire lines and wire tensioning increased the mechanical reliability of the fence structure and the renewable energy subsystem provided the electrical energy needed for the energizer and IoT monitoring unit.

The experimental results revealed that the wind turbine output was 4.92-8.37 W, solar panel output was 7.61-26.77 W and the hybrid system output was 21.97-27.80 W. These results indicate that the solar PV made the highest single contribution in ideal daylight hours while the wind turbine acted as a supplementary power source when wind was present. The hybrid configuration had the most stable voltage range of 12.35-12.93 V, and the highest maximum output of 27.80 W. This indicates that using both sources is beneficial for decreasing reliance on one resource and can enhance the stability of the electricity supply for smart electric fence systems.

The ESP32 and Blynk monitoring subsystem also showed the real-world benefits of remote voltage monitoring. The mobile dashboard and alert feature allows users to keep track of the battery's status and take action once the voltage level is reached. This is to decrease the need for people to manually check the fence system regularly and to improve awareness of the condition of the fence system. Hence the proposed system is a low cost and practical solution for the rural farm security where the electricity grid is limited.

In this study, however, short-term experimental testing only was performed and the results were reported as measured ranges, instead of averaged controlled repetitions. This phase did not involve long-term exposure to the outdoors, repeated controlled environmental testing, response when tested with animals, or detailed statistical analysis. Further testing should incorporate long-term field testing, data logging, multiple testing, standard deviation analysis and comparison, and testing under various loading and weather conditions. In conclusion, the study demonstrates that the combination of solar power and wind energy with IoT monitoring system can enhance the reliability and usability of smart electric fencing for agricultural protection.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Author Contribution

Muhammad Azim Zulraihan bin Zulkainain contributed to the study conception and design, system fabrication, data collection, analysis and manuscript preparation. Salihatun binti Md Salleh contributed to supervision, project guidance, review and editing. All authors reviewed the results and approved the final version of the manuscript.

Ethics Committee Approval

Not applicable. This study did not involve human participants, animals as experimental subjects, clinical samples or personal data collection.

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