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Off-Grid Savonius Wind-Powered Street Lighting with Cascading Logic

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ABSTRACT

This research addresses the limited electrical lighting on rice-field pathways in Munggugianti Village, Gresik, which creates safety risks for residents and farmers at night. The study aims to design and implement an off-grid wind-powered public street lighting system and evaluate its energy efficiency using a cascading control method. A quantitative experimental approach was applied using an ESP32 microcontroller, a four-blade Savonius wind turbine coupled to a 60 W DC generator, six HC-SR501 PIR sensors, and PZEM-017 electrical sensors. Electrical parameters were monitored in real time through ThingSpeak, while field measurements were conducted over 24-hour cycles for seven days. The system harvested energy under wind speeds from 0.9 to 4.2 m/s and achieved a peak charging power of 11.75 W. The ESP32 control successfully activated the lamps sequentially according to detected motion, with a reported precision of 100%. The cascading mode reduced the load from a peak of 62.04 W during full-on operation to 1.69–5.08 W and reached 0 W when no movement was detected late at night. These results indicate that integrating the Savonius turbine with intelligent cascading control can improve energy utilization in off-grid pathway lighting.
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1. INTRODUCTION

Reliable nighttime lighting is important for pathways in rural areas where access to grid electricity is limited. The final-project proposal identifies the rice-field pathway in Munggugianti Village, Benjeng, Gresik as the study location and develops an independent Pembangkit Listrik Tenaga Bayu (PLTB) system to provide pathway illumination. The proposal uses a Savonius vertical-axis wind turbine because vertical-axis configurations are suitable for wind conditions with changing direction and can be applied to low-speed wind environments. [1]

The proposed generation subsystem uses a four-blade Savonius turbine coupled to a 60 W DC generator. The design calculation in the proposal uses a power coefficient of 0.2 and a design wind speed of 5 m/s, resulting in a calculated swept area of approximately 3.89 m² and final blade dimensions of approximately 111 cm in height and 56 cm in diameter. The system stores the generated energy in a LiFePO4 battery before it is supplied to the lighting and control loads. The proposal also identifies LiFePO4 as the selected storage technology for the off-grid system. [2]

Energy utilization is a key consideration in the proposed off-grid lighting system because the stored energy must support the lamps and control electronics. To reduce unnecessary lighting operation, the system applies PIR-based automatic control. The proposal uses six HC-SR501 PIR sensors distributed across three lighting zones. PIR-based energy-saving operation has also been applied in previous work using the HC-SR501 sensor. [3] The operating schedule is referenced by an RTC DS3231 so that the system can distinguish the full-lighting period from the energy-saving period. [4]

The proposed system further integrates an ESP32 as the main controller and uses electrical monitoring to observe both the energy-harvesting and lighting-load sides. The ESP32 is used to process sensor inputs and control the lighting sequence, while real-time sensor-network operation is supported by the characteristics discussed in the proposal. [5] For remote monitoring, the measured electrical parameters are transmitted to the ThingSpeak platform; the proposal cites ThingSpeak as an IoT platform that can be used for lighting-control and monitoring applications. [6] The PZEM-017 measurements are communicated through an RS-485/Modbus interface, for which the proposal also includes a reference discussing acquisition-time optimization in Modbus communication. [7] Based on these considerations, this research designs, implements, and evaluates an off-grid Savonius wind-powered street lighting system using cascading logic to activate the lamps according to detected movement while monitoring electrical parameters remotely.

2. METHOD

The research used a quantitative experimental approach. The work was conducted in the rice-field pathway area of Munggugianti Village, Benjeng, Gresik. The research sequence consisted of literature study, problem identification and formulation, site observation, analysis and identification of tools and materials, equipment design, equipment testing, data acquisition and analysis, and report preparation. The complete systematic flow of this methodology is illustrated in Figure 1. If a trial was unsuccessful, the process returns to the equipment-design stage before retesting.

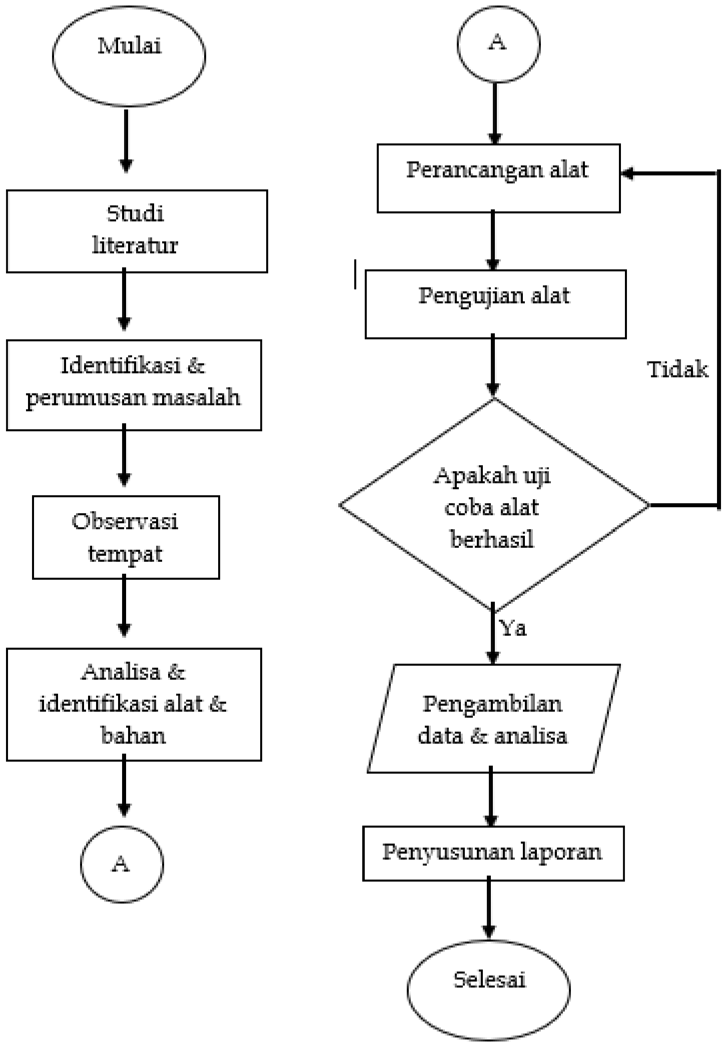

Figure 1. Research-method flowchart

2.1 System Design

The energy path begins with the Savonius turbine and DC generator. Generated electrical energy is regulated by the charge controller and stored in a LiFePO4 battery. From the battery, one path supplies the control and communication electronics through a buck converter, while another path supplies the three PJU lamps through a three-channel relay. The ESP32 receives time information from the RTC DS3231 and motion information from six PIR sensors. Two PZEM-017 units are placed on the input and output sides so that electrical parameters can be monitored separately. Communication between the PZEM-017 units and ESP32 uses an RS-485-to-TTL module, while a modem provides the internet connection to ThingSpeak. The complete electrical connections of these components are illustrated in the single-line diagram shown in Figure 2.

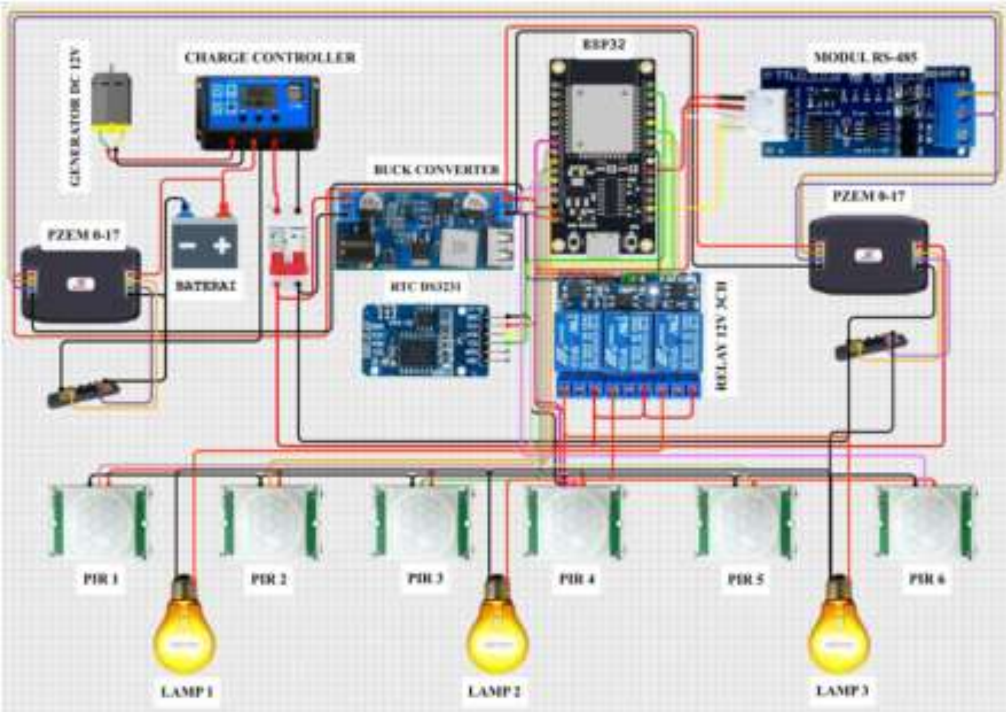

Figure 2. Single-line diagram of the PJU system

2.2 Component Sizing and Design Calculation

The lighting load was designed around three 9 W lamps. The proposal calculates the lamp load as 3 × (12 V × 0.75 A) = 27 W. The calculated auxiliary loads are 0.6 W for the ESP32, 0.00099 W for the RTC DS3231, 1.05 W for the three-channel relay, 0.0078 W for six PIR sensors, 0.2 W for two PZEM-017 units, 0.05 W for the RS-485 module, and 1.0 W for the USB modem. The resulting total system load used in the proposal is 29.90879 W, corresponding to a calculated daily energy requirement of 381.21 Wh.

$$E\_daily = 381.21 \text{ Wh} \quad (1)$$

The battery capacity was calculated from the daily energy requirement, a 12 V system voltage, 80% depth of discharge, and 80% system efficiency:

$$C\_batt = 381.21 / (12 \times 0.8 \times 0.8) = 49.6367 \text{ Ah} \approx 50 \text{ Ah} \quad (2)$$

The charge-controller requirement was calculated as:

$$I\_CC = 381.21 / 12 = 31.7675 \text{ A} \approx 40 \text{ A} \quad (3)$$

With an assumed average usable wind period of eight hours per day and a system efficiency of 80%, the proposal calculates the required turbine-side energy as 476.512 Wh and the required generator power as 59.564 W. The selected generator therefore has a capacity of 60 W and a 12/24 V operating specification.

$$P\_in = ½ \rho A v^3 \quad (4)$$

where P_in is wind-capture power, A is the blade swept area, v is wind speed, and ρ is air density as used in the proposal.

$$P\_out = \tau\omega \quad (5)$$

Using the design power of 59.564 W, a power coefficient of 0.2, air density of 1.225 kg/m³, and design wind speed of 5 m/s, the proposal obtains a required swept area of approximately 3.89 m². The resulting blade dimensions are approximately 1.112 m in height and 0.556 m in diameter, rounded in the proposal to 111 cm and 56 cm.

2.3 Control Logic and Data Acquisition

The ESP32 firmware is organized as a state-machine approach covering standby, full-on, and cascading operating states. According to the design, the lamps operate in full-on mode from 17:30 to 21:00 and then enter energy-saving mode based on PIR detection until 05:00. The RTC DS3231 supplies the operating-time reference. During cascading operation, the six PIR sensors represent three lighting zones. When an object enters a zone, the ESP32 commands the relay to illuminate the appropriate lamps; when movement is absent for more than two seconds, the lamps return to standby. The design also supports movement in the opposite direction.

Electrical measurements are acquired from PZEM-017 sensors through RS-485 communication. The monitored parameters are voltage, current, power, and accumulated energy. Data are transmitted to ThingSpeak through the internet modem for real-time observation. Field testing was performed using 24-hour cycles over seven days, covering energy input from the turbine/generator, generator-voltage comparison, energy output at the lighting load, and functional testing of the cascading logic.

3. RESULTS AND DISCUSSION

3.1 Hardware Realization

The implemented hardware is divided into the generation unit, storage and distribution unit, and control and monitoring unit. The generation unit consists of a four-blade Savonius turbine made from sheet material and directly coupled to a 60 W DC generator. The realized turbine uses the final dimensions reported in the results section, approximately 111 cm blade height and 56 cm blade diameter. The turbine is installed on the main support pole in the rice-field pathway area. The physical realization of this generation unit is shown in Figure 3.

Figure 3. Realized four-blade Savonius turbine and DC generator

The storage and distribution unit uses a 12 V/24 V charge controller, a LiFePO4 battery reported as 50 Ah in the sizing and realized-system sections, DC MCB protection, and a buck converter. The control and monitoring unit contains the ESP32, RTC DS3231, six PIR sensors, a three-channel relay, two PZEM-017 sensors, an RS-485 module, and an internet modem.

Figure 4. Installation of components inside the control panel

The storage and distribution unit uses a 12 V/24 V charge controller, a LiFePO4 battery reported as 50 Ah in the sizing and realized-system sections, DC MCB protection, and a buck converter. The control and monitoring

unit contains the ESP32, RTC DS3231, six PIR sensors, a three-channel relay, two PZEM-017 sensors, an RS-485 module, and an internet modem. The installation of these components inside the control panel is depicted in Figure 4

Figure 5. Realized PJU lamp pole and PIR sensor modules

3.2 Energy Input and Wind-Energy Harvesting

Field measurements from 27 July to 2 August 2026 show that the Savonius system continued to harvest energy under changing wind conditions. The overall wind-speed range reported in the proposal was 0.9–4.2 m/s. The highest charging power was 11.75 W, recorded on 28–30 July during the higher-output measurement periods. On 31 July and 1 August, the peak input power was lower, at 7.06 W and 6.96 W respectively, reflecting the reported lower wind intensity. On 2 August, the peak input power was 6.80 W. **A** summary of these peak energy-input power values over the seven-day test is presented in Table 1.

Date	Peak input power (W)	Reported observation
27-07-2026	11.66	Highest during 18:00–20:00
28-07-2026	11.75	Highest during 18:00–20:00
29-07-2026	11.75	Stable high output
30-07-2026	11.75	Peak during 18:00–19:00
31-07-2026	7.06	Lower output under fluctuating wind
01-08-2026	6.96	Moderate/lower wind condition
02-08-2026	6.80	Lower output, continuous harvesting

Table 1. Summary of reported peak energy-input power during the seven-day test

The charging voltage was generally regulated by the charge controller. The proposal reports a stable charging range of 13.21–13.30 V in the principal analysis of the energy-input tests, while later test periods also record lower values when the system condition changed. Comparison of generator-terminal voltage measured with a multimeter and the charge-controller reading showed small differences, generally around 0.1–0.2 V in the reported measurements. On 31 July, for example, the maximum wind speed was 4.2 m/s and the generator-terminal voltage reached 14.1 V, while the charge-controller reading was 13.9 V. On 1 August, the lowest measured wind speed was 0.9 m/s and the multimeter voltage was 4.0 V, whereas the peak voltage reached 13.9 V at 3.9 m/s. These observations support the relationship reported in the proposal between changing wind speed and generator voltage.

3.3 Load-Side Energy Consumption and Cascading Performance

The load-side measurements demonstrate the operating transition created by the control program. During the full-on period, all three lamps operate simultaneously from approximately 18:00 to 20:00. The highest recorded load was 62.04 W on 31 July, with 4.91 A. After 21:00, the system changes to cascading mode, where the load decreases according to detected movement. The proposal reports cascading-mode values between 1.69 W and 5.08 W, and 0 W when no movement is detected during quiet late-night periods. These recorded values for full-on peak and cascading modes are summarized in Table 2.

Date	Full-on peak (W)	21:00 cascading (W)	Late-night condition
27-07-2026	61.95	2.34	≈0 W at 22:00–23:00
28-07-2026	61.43	5.08	0 W at 22:00–23:00
29-07-2026	61.14	2.11	0 W at 22:00–23:00
30-07-2026	61.43	5.08	0 W at 22:00–23:00
31-07-2026	62.04	1.69	0.48–1.58 W at 22:00–23:00
01-08-2026	56.96	2.05	0 W at 22:00–23:00
02-08-2026	43.41	1.86	<2 W through 23:00

Table 2. Reported load-side peak and cascading-mode power values

The seven-day load measurements show a repeated operating pattern. On 27 July the load reached 61.95 W at 20:00 and fell to 2.34 W at 21:00. On 28 July, the full-on load reached 61.43 W and the cascading value at 21:00 was 5.08 W, followed by 0 W when the pathway was empty. On 29 July, the peak was 61.14 W and the 21:00 cascading value was 2.11 W. The 30 July peak was 61.43 W, with 5.08 W in cascading mode at 21:00. The highest full-on value of the test, 62.04 W, occurred on 31 July, while the 21:00 value fell to 1.69 W. On 1 August the peak was 56.96 W and the 21:00 value was 2.05 W. On 2 August, the full-on value was lower at 43.41 W and the cascading value at 21:00 was 1.86 W.

These measurements directly support the proposal's main energy-management finding: keeping the three lamps fully illuminated creates a substantially larger instantaneous load than activating only the lighting required by the detected movement. The cascading logic also prevents unnecessary late-night consumption because all lamps can return to the off state when the PIR sensors no longer detect movement.

3.4 Functional Test of the Cascading Logic

The functional test covered eleven scenarios involving no object, entry through Zone 1, movement through Zone 2 and Zone 3, movement in the reverse direction, and departure from the pathway. The six PIR inputs were arranged over three lighting zones. The reported test result was 100% successful, with no reading error or response delay. When an object entered Zone 1, Lamps 1 and 2 were activated. When the object moved toward Zone 2, Lamp 1 was turned off while Lamps 2 and 3 remained on. At Zone 3, the lighting shifted so that the appropriate downstream lamps remained active. The same cascading behavior was reported for movement in the opposite direction.

A two-second delay-off function was also validated. When movement was absent for more than two seconds, the relay returned the lighting system to the standby condition and all three lamps were turned off. This function is important for the off-grid configuration because it removes unnecessary load after the object leaves the detection area.

3.5 IoT Monitoring

The monitoring subsystem provides real-time visibility of the input and output electrical parameters. PZEM-017 sensors are connected through the RS-485-to-TTL communication interface to the ESP32, and the measured voltage, current, power, and accumulated-energy values are transmitted to ThingSpeak through the internet modem. The proposal uses separate input and output monitoring so that energy entering the storage system can be compared with the electrical behavior of the lighting load.

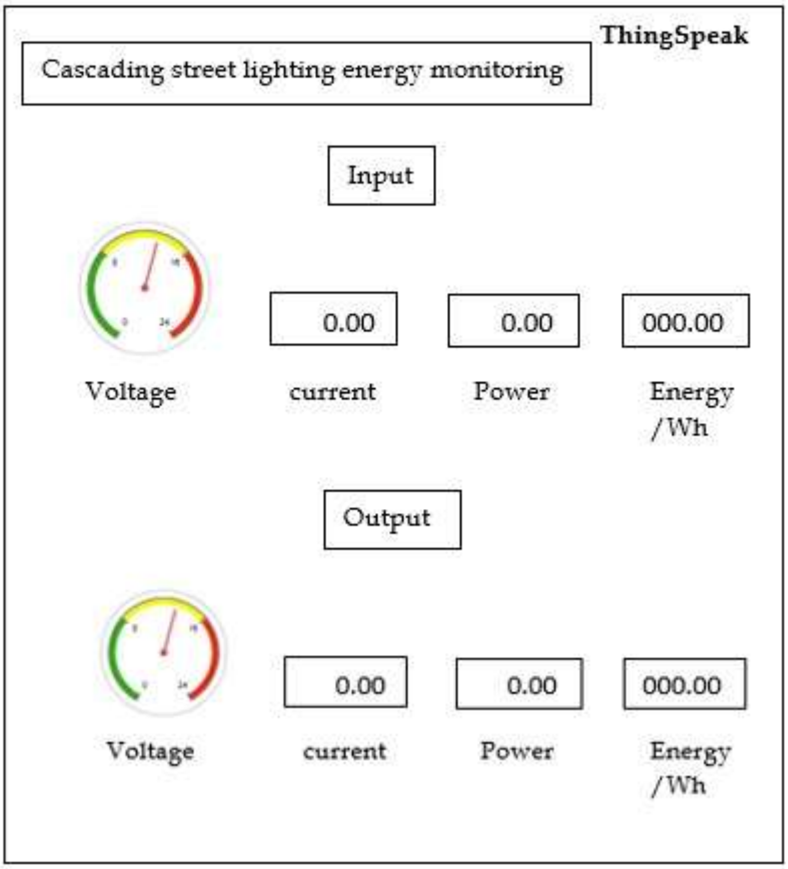

Figure 6. ThingSpeak dashboard used for input and output energy monitoring

4. CONCLUSION

The off-grid street-lighting system based on a four-blade Savonius turbine, ESP32 control, PIR detection, and real-time electrical monitoring was successfully realized and tested in the rice-field pathway area of Munggugianti Village, Gresik. The system harvested energy over the reported wind-speed range of 0.9–4.2 m/s and achieved a maximum charging power of 11.75 W. The generator-voltage tests showed a small difference between multimeter and charge-controller readings, generally around 0.1–0.2 V in the reported measurements. The ESP32 and six PIR sensors successfully implemented the cascading sequence with a reported functional-test success rate of 100%. The control shifted lighting according to object position and returned the lamps to standby after more than two seconds without movement. From a load-management perspective, the system demonstrated a significant reduction in instantaneous power demand; the full-on load reached 62.04 W, whereas the instantaneous power drawn during cascading mode dropped to the range of 1.69–5.08 W, and even reached 0 W when the pathway was empty. The results therefore show that the proposed cascading strategy effectively minimizes unnecessary instantaneous power draw, thereby supporting a more efficient use of the stored energy in the off-grid system.

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