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Application of a Horizontal Wind Turbine for Street Lighting: An Alternative Renewable Energy Source

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ABSTRACT

This study explores the development and evaluation of a horizontal axis wind turbine system as an alternative energy source for street lighting applications. The system comprises a wind-driven DC generator, a battery (accumulator) for energy storage, and an inverter to convert DC to AC power for lighting use. Three main performance tests were conducted: generator voltage testing, battery charging analysis, and battery discharge under lighting load. Generator testing revealed that output voltage varied with wind velocity, reaching a peak of 22.57 V at 14:00, indicating optimal turbine performance during high wind periods. The charging test demonstrated effective voltage transfer to the battery, with voltage increasing from a low state of charge to a full 12.64 V over a 6.5-hour period. The charging current and power also showed consistent growth, confirming efficient energy storage. During the load test, the battery successfully powered a streetlamp for approximately 5 hours, maintaining a voltage range between 12.64 V and 10.97 V. The system delivered an average power output of 3.20 W and light intensity of 1150 lux. The use of LTC3780 and XH-M604 control modules proved effective in stabilizing voltage input and managing battery charge cycles to prevent overcharging or deep discharge, thereby improving system reliability and battery lifespan. Overall, the results confirm that a horizontal wind turbine system can be effectively utilized for street lighting, especially in remote or off-grid areas, contributing to the development of sustainable and independent energy infrastructure.

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1. INTRODUCTION

Wind is a collection of air that experiences movement due to pressure differences that are on the surface of the earth. The wind moves from areas of high pressure to areas of low pressure. Transforming wind as renewable energy into electrical energy for lighting can create innovative solutions that improve productivity and everyday use [1]. The growing demand for energy in Indonesia has become a critical factor in supporting the socio-economic development. Electrical energy now constitutes an indispensable element of daily life, driven by rapid advancements in technology, industrialization, and information systems. However, the nation continues to rely heavily on fossil fuels, especially petroleum and coal, as the primary source of electricity generation. The limitation of fossil fuel reserves, and environmental hazards are serious challenges to energy sustainability.

The growing global demand for sustainable and clean energy sources has intensified interest in renewable energy technologies, with wind energy emerging as a key contributor. Recent studies underscore the adaptability of wind power generation in various environments, from high-density urban areas to remote coastal and desert regions. For instance, Datta et al. [2] explored the unconventional potential of indoor wind energy harvesting using ceiling fans to generate electrical energy for lighting without drawing on conventional power sources, demonstrating the feasibility of wind utilization in everyday environments. Similarly, Gannavaram et al. [3] highlighted the innovative integration of ambient energies—such as wind and sound—within populated areas to produce electricity, emphasizing the significance of energy conversion in urban sustainability strategies. In coastal Indonesia, Siagian et al. [1] applied Savonius-type turbine technology to effectively harness low-speed winds at Wong Polo Beach, providing a practical solution for decentralized energy generation in rural communities. Complementing these efforts, Cherki et al. [4] investigated the wind energy potential in the Kaberten region of Southern Algeria, showing that even arid and remote areas can substantially benefit from localized wind exploitation. These diverse applications illustrate the scalability and versatility of wind energy systems, positioning them as a crucial component of future energy infrastructures.

The integration of wind turbines into lighting systems, particularly for street lighting, has emerged as a viable and sustainable solution to address growing energy demands while reducing environmental impacts. Small-scale wind turbines have proven effective in powering lighting infrastructure in both urban and remote areas [5]. In Indonesia, where electrification in rural and coastal regions remains a challenge, wind energy has been identified as a potential renewable resource to supplement conventional power supply, enhancing community access to reliable lighting [6], [7]. Several studies have focused on the deployment of vertical axis wind turbines (VAWTs), which are well-suited for urban environments due to their compact design and ability to harness wind from multiple directions [8], [9]. These systems can also capture wind energy generated by the motion of vehicles along highways, providing a continuous power supply for adjacent lighting systems [10]. Innovations such as the twisted Savonius turbine have shown promising performance in small-capacity applications for lighting towers [11]. The combination of wind energy with smart lighting controls and IoT technologies further enhances efficiency and fault detection capabilities [12], [13]. Additionally, hybrid systems incorporating solar and wind energy offer increased reliability for lighting applications, especially in regions with variable wind conditions [14], [15]. These advancements not only contribute to energy conservation but also support climate change mitigation by reducing greenhouse gas emissions associated with conventional lighting [16].

Despite the extensive research on wind energy and its integration into lighting systems, a noticeable gap remains in the practical application and optimization of horizontal wind turbines (HWTs) for street lighting, particularly within the Indonesian context. Most existing studies have concentrated on vertical axis wind turbines (VAWTs) due to their suitability for turbulent urban wind conditions, leaving the potential of HWTs underexplored. This is especially relevant given that HWTs, when properly sited, can offer higher efficiency in capturing consistent wind flows common in certain rural and coastal regions of Indonesia. Moreover, there is limited empirical data on the performance, design adaptations, and cost-effectiveness of small-scale HWT systems tailored for street lighting applications. Therefore, this study aims to bridge these gaps by investigating the utilization of horizontal wind turbines as an alternative energy resource for street lighting. The research will evaluate the technical feasibility, environmental benefits, and implementation challenges of HWT-based systems, with the goal of developing a sustainable and scalable model that supports Indonesia's transition to cleaner energy and improved rural electrification.

2. METHOD

Figure 1 describes a schematic illustration of the possible configuration of a wind-powered street lighting system, starting with a horizontal-axis wind turbine (rated at 10 Watts at a wind speed of 12 m/s) that captures wind energy and converts it into mechanical motion. This motion drives a 24V DC generator, producing electrical energy. The generated voltage is then stabilized by the LTC3780 module, which ensures a consistent output regardless of wind speed fluctuations. The regulated voltage is directed to an accumulator for storage, specifically a 12V 7Ah sealed lead-acid (SLA) battery. To protect the battery and manage its charging process, the HX M604 module is used, preventing overcharging or deep discharge. When energy is needed to power the streetlights, the stored DC voltage from the accumulator is converted into AC using a DC-to-AC inverter, making it compatible with standard AC lamps. This arrangement provides an efficient and self-sustaining lighting system, particularly suitable for areas with limited grid access or as a renewable backup during outages.

DC generator voltage testing was conducted to measure the output voltage generated by the wind turbine under varying wind velocities throughout the day. The test began with the installation of a wind turbine in an open outdoor area with consistent wind exposure, connected to a DC generator. A digital multimeter or data logger was used to measure and record the output voltage and current at regular intervals, while an anemometer placed at 2.35 meters, the same height as the turbine blades measured wind speed in meters per second. Data was collected every 30 minutes from morning to evening, capturing changes in both wind speed and voltage output. All measurements were logged for analysis, allowing researchers to examine the correlation between wind velocity and generator output, and assess the generator's performance in converting wind energy into electrical energy.

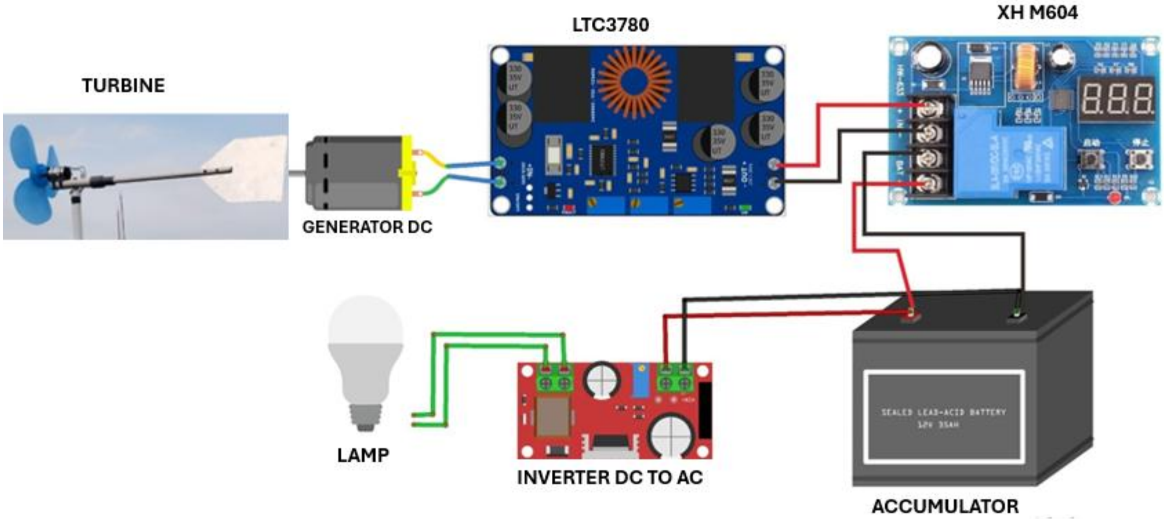

Figure 1. Schematic Diagram of Wind -Powered Street Lighting System

An accumulator (battery) charging test was performed to observe the voltage transfer and charging efficiency from the generator to the battery by connecting the DC generator output to the battery through a charge controller, such as the XH-M604 module, which regulates charging to prevent overcharging or deep discharging. During the test, voltage at both the generator terminal (Vt) and battery terminal (Vb) was measured and recorded at regular intervals, typically every 30 minutes, using a multimeter or data logger. The charging current (Ib) and power (Pb) were also monitored to evaluate how effectively the generator delivered energy to the battery. The battery's state of charge (SoC) was tracked throughout the charging period to determine how quickly and efficiently it reached full capacity under variable wind conditions. This setup helped in assessing both the performance of the generator and the effectiveness of the charging control system in real-time conditions. As the system uses a sealed lead-acid (SLA) battery, the SoC was approximated based on the open-circuit voltage (OCV) method, referencing standard SLA battery voltage–SoC curves. While Coulomb counting provides more accurate SoC estimation by tracking the charge and discharge currents over time, the chosen approach prioritizes simplicity and cost-efficiency. This limitation has been noted as an area for improvement in future work.

The accumulator loading test was carried out by connecting the charged battery to a lighting load, during which the battery's discharge performance was analyzed. This test included monitoring the battery voltage during discharge, power supplied to the lamp, light intensity in lux, and the battery's remaining SOC over a 5-hour operation period

3. RESULTS AND DISCUSSION

3.1 DC Generator Voltage Testing

This test or measurement is carried out to find out the extent to which the wind speed can move the DC generator to produce a DC voltage to be used as a lighting system. This test is carried out once every 30 minutes, because wind speed can change significantly in a short period of time. By taking measurements every 30 minutes, significant changes in wind speed can be detected and recorded. The following table 1. DC generator voltage measurement test results based on wind speed. The table 1 illustrates the correlation between wind velocity, output voltage, and current generated by a wind turbine system throughout the day, from 06:00 to 18:00. In the early morning hours, wind speed remain low (below 2.0 m/s), resulting in minimal voltage and no current generation. Notable power generation begins after 08:00, coinciding with increased wind speeds exceeding 2.0 m/s. A significant rise in performance is observed from 10:00 onward, with the highest voltage output of 22.57 V and peak current of 0.05 A occurring at 14:00 when the wind speed reaches its maximum of 4.1 m/s. Current output remains consistent between 0.01 A and 0.05 A, primarily during periods of wind velocity above 2.5 m/s. This data demonstrates a strong positive correlation between wind speed and electrical output, highlighting the turbine's operational efficiency during midday to late afternoon. It also indicates that the system requires a minimum wind threshold of approximately 1.5–2.0 m/s to initiate meaningful energy production, emphasizing the potential need for energy storage or hybrid solutions to maintain power availability during low-wind periods.

Table 1 data of DC Generator voltage measurement

Hour	Wind speed (m/s)	Output Voltage (V)	Current (A)
06:00	0,5	-	-
06:30	0,8	-	-
07:00	1,5	4,88	-
07:30	0,7	-	-
08:00	2,3	13,94	0,01
08:30	1,8	6,93	-
09:00	1,8	6.32	-
09:30	0,9	-	-
10:00	3,1	18,33	0,03
10:30	1,8	5,47	-
11:00	2,2	12,87	0,03
11:30	2,6	14,45	0,03
12:00	2,1	13,61	0,02
12:30	1,6	5,11	-
13:00	2,8	14,67	0,03
13:30	3,7	20,14	0,05
14:00	4,1	22,57	0,05
14:30	3,1	18,48	0,03
15:00	2,1	13,51	0,02
15:30	2,8	14,60	0,03
16:00	2,3	13,90	0,03
16:30	3,4	19,89	0,04
17:00	3,8	20,98	0,05
17:30	4,0	22,01	0,05
18:00	3,1	18,93	0,04

3.2 Accumulator (battery) Charging Test

This test is carried out to determine the extent of the generator's performance in providing voltage to the accumulator. This voltage measurement is carried out based on the length of voltage provided by the generator to the accumulator. The following table 2 shows the voltage measurement of the accumulator when given a load:

Table 2. Generator to accumulator voltage testing

Time	Vt (V)	It (A)	Pt (W)	Vb (V)	Ib (A)	Pb (W)	SOC
10:00	18,33	0,03	0,54	10,57	0,06	0,84	3%
10:30	5,47	0,01	0,05	10,83	0,07	0,85	15%
11:00	13,87	0,03	0,41	10,97	0,07	0,85	22%
11:30	14,45	0,03	0,43	11,17	0,08	0,99	31%
12:00	13,61	0,02	0,27	11,28	0,06	0,74	37%
12:30	5,11	0,01	0,05	11,42	0,06	0,75	43%
13:00	14,67	0,03	0,44	11,57	0,07	0,88	50%
13:30	20,14	0,05	1,00	11,65	0,08	0,93	54%
14:00	22,57	0,05	1,11	11,87	0,07	0,83	65%
14:30	18,48	0,03	0,55	11,98	0,07	0,84	70%
15:00	13,51	0,02	0,27	12,28	0,08	0,98	84%
15:30	14,60	0,03	0,43	12,46	0,07	0,87	93%
16:00	13,90	0,03	0,42	12,57	0,07	0,88	98%
16:30	19,89	0,04	0,79	12,64	0,07	0,89	100%

The table presents the performance data of a wind-powered generator system charging an accumulator (battery) over time, measured from 10:00 to 16:30. The column labeled ‘t’ refers to the turbine terminal, while ‘b’ denotes the battery terminal. Throughout the day, Vt (turbine voltage) increases steadily, with peak values observed in the afternoon at 14:00 with 22.57 V and the lowest at 12:30 with 5.11 V. This observed indicating the impact of fluctuating wind conditions. Simultaneously, Vb (battery voltage) also rises, though at a slower rate due to battery charging dynamics, eventually reaching a maximum of 12.64 V at 16:30. The charging current (Ib) and power (Pb) show a consistent increasing trend, reflecting effective energy transfer from the generator to the battery. As a result, the State of Charge (SOC) improves progressively from 3% to 100%, illustrating the system's capability to convert wind energy into storable electrical energy efficiently. Based on the measurements, the average increase in SOC is approximately 0.69% every 30 minutes, demonstrating steady and reliable charging performance throughout the observed period.

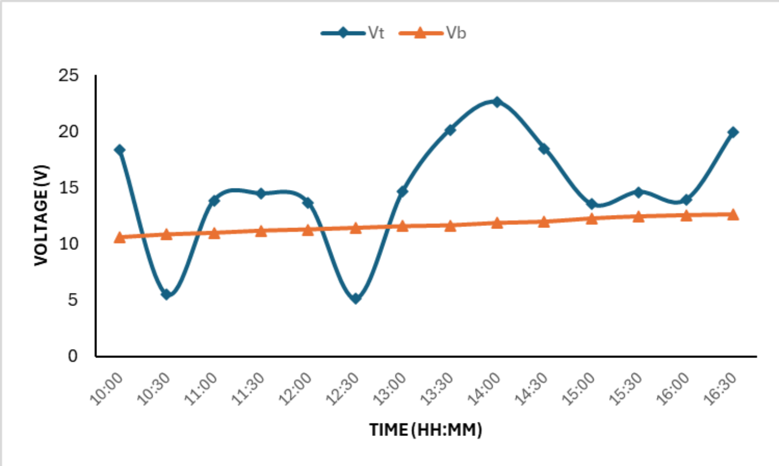

Figure 2. comparison voltage in turbine (Vt) and battery (Vb)

The graph illustrates the voltage comparison between the turbine terminal (Vt) and the battery terminal (Vb) over time, from approximately 10:00 to 16:30. The Vt line exhibits significant fluctuations, indicating variable wind input affecting the turbine's performance, with noticeable peaks at around 13:30 (above 22 V) and 16:30 (around 20 V), and dips near 10:30 and 12:30 (close to 5 V). In contrast, the Vb line shows a steady, gradual increase, reflecting the charging process of the battery, which rises smoothly from about 10.5 V to over 12.5 V. This trend highlights the system's effective energy conversion despite inconsistent generator output, as the battery voltage consistently climbs, demonstrating stable storage and regulation of the incoming energy.

3.3 Accumulator loading test on load

This test is conducted to evaluate the performance of the accumulator in supplying voltage to the load. The voltage measurement is based on the duration and consistency of the voltage delivered by the accumulator to the load. Table 3 is the result of measuring the accumulator voltage when given a load.

Table 3. Voltage testing from accumulator to load.

Time	Vb (V)	Ib (A)	Pb (W)	V Load (V)	I Load (A)	P Load (W)	SOC	Light Intensity (Lux)
17:00	12,64	0,57	6,80	220,04	0,02	4,40	100%	1159
17:30	12,24	0,52	6,18	220,01	0,01	2,20	82%	1098
18:00	11,82	0,48	5,60	220,05	0,01	2,20	62%	1140
18:30	11,71	0,47	5,54	220,03	0,02	4,40	57%	1124
19:00	11,56	0,49	5,75	220,03	0,02	4,40	50%	1151
19:30	11,38	0,50	5,84	220,02	0,01	2,20	41%	1177
20:00	11,29	0,40	4,57	220,01	0,01	2,20	37%	1190
20:30	11,20	0,40	4,48	220,02	0,02	4,40	33%	1152
21:00	11,15	0,41	4,57	220,03	0,01	2,20	30%	1126
21:30	11,03	0,38	4,19	220,03	0,01	2,20	25%	1163
22:00	10,97	0,38	4,16	220,04	0,02	4,40	22%	1170

The table displays the discharge performance of an accumulator (battery) when supplying power to a load from 17:00 to 22:00, along with ambient light intensity measurements. Initially, at 17:00, the battery voltage is highest at 12.64 V with a current of 0.57 A and power of 6.80 W, and the SOC is at full capacity (100%). As time progresses, both battery voltage and output power gradually decrease, reflecting the reduction in stored energy, with the SOC dropping to 22% by 22:00. Meanwhile, the load voltage remains stable at around 220 V, and the power delivered to the load fluctuates between 2.20 W and 4.40 W, depending on the current drawn.

Light intensity values fluctuate slightly throughout the evening, generally remaining above 1100 Lux, indicating a consistent lighting level during the battery discharge period.

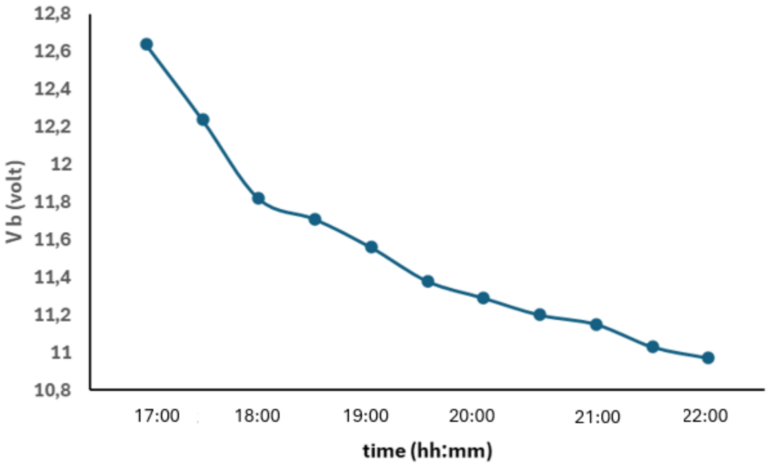

Figure 3. correlation of time and battery voltage

In Figure 3, a clear downward trend in battery voltage (Vb) is observed from 17:00 to 22:00, dropping from approximately 12.7 V to around 10.9 V. This steady decline indicates the gradual depletion of the accumulator's charge as it continues to supply power to the load. The consistent voltage drop reflects typical battery discharge behavior, where the voltage decreases as the State of Charge (SOC) reduces. This also demonstrates that the battery was actively powering the load during this period, gradually delivering stored energy. Despite the ongoing discharge, the battery maintained a stable output for several hours, which suggests good initial performance and capacity.

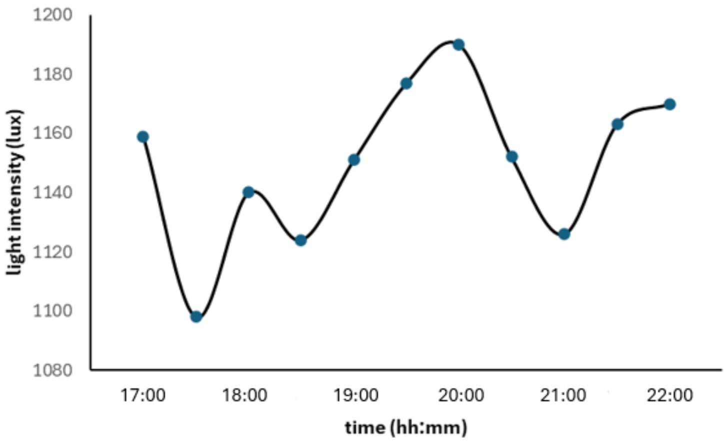

Figure 4. Correlation of time and light intensity

Figure 4 illustrates the correlation between time and light intensity during the battery discharge phase from 17:00 to 22:00. The light intensity, measured in lux, fluctuates throughout this period, ranging from a low of approximately 1090 lux to a peak of around 1190 lux. These variations likely result from environmental changes such as cloud cover, sunset progression, or interference from artificial lighting sources. Although the values remain relatively high and within a narrow range, the non-linear pattern suggests that light intensity during this period is unstable and not consistently decreasing, as might be expected after sunset.

This fluctuation in light intensity is important when evaluating the lighting system's performance, especially in relation to the energy source. Despite the declining State of Charge (SOC) in the battery, as seen in the earlier data, the lighting system continues to function effectively, maintaining acceptable illumination levels. This indicates that the accumulator still provides sufficient power to meet lighting demands, even as its voltage drops. Furthermore, the light intensity does not show a direct correlation with battery voltage over this period. Instead, it suggests that the lighting system is well-regulated, likely through a constant power control mechanism, ensuring stable illumination regardless of minor dips in voltage. This performance is critical for real-world applications where consistent lighting is needed, such as in street lighting or off-grid solar-powered systems. Therefore, Figure 4 supports the conclusion that the system can maintain functional lighting levels even as battery energy depletes, reflecting good energy management and design efficiency.

4. CONCLUSION

Based on the research, several important conclusions can be drawn related to the design of a wind power generation system for street lighting:

1. System Design: The wind-powered street lighting system has been successfully designed and implemented, utilizing a horizontal-axis wind turbine, DC generator, battery storage, and inverter to supply AC power to the lights, which operated for up to 5 hours during testing with an average light intensity of 1150 lux. However, data shows that the turbine's charging power never exceeded 2 Watts, while the average load demand was 3.20 Watts, indicating a clear power deficit. Under the current configuration and wind conditions, the system is not sustainable, highlighting the need for improvements such as a higher-capacity turbine, integration of additional energy sources like solar panels, or deployment in areas with stronger and more consistent wind.
2. Lamp Lighting Efficiency: The use of LTC3780 and XH M604 Battery Charge Control modules proved effective in maintaining battery voltage stability. The LTC3780 module functions as a voltage stabilizer from the generator, while the XH M604 controls the charging of the battery to avoid overcharge or discharge which can reduce the life of the battery. Thus, the lighting efficiency of the lamp can be optimized.
3. Voltage Distribution: The voltage distribution system from the wind turbine to the streetlights has been successfully implemented. The voltage generated by the wind turbine is regulated and stored in the accumulator, then converted into AC voltage by the inverter. This AC voltage is then distributed to the street lighting lamps through cables. From the study, the voltage distribution for lamp usage for 5 hours from the voltage distributed by the accumulator is 12.64 Volts to 10.97 Volts.

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