Wind Energy Harvesting for Street Lighting

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Abstract-- The researchers and urban planners have been encouraged to look for the alternatives capable of supporting public infrastructure namely street lighting systems by the rising sustainable and decentralized energy solutions demand. Typical street lighting uses the grid electricity which considerably raises energy consumption, carbon emissions and susceptibility to frequent supply disruptions. The challenges are identified as the concerns and hence the current study looks into the integration of Vertical Axis Wind Turbines (VAWTs) directly mounted on existing streetlight poles as an independent power source for smart urban lighting in terms of feasibility and benefits. VAWTs have several advantages in urban areas because of their capability to capture wind from all directions, simple mechanical design, and as being able to work effectively with low wind speeds. The studies show that such turbines have very low cut-in speed and can provide steady output power even with turbulent or slow-moving urban airflows. Those features turn VAWTs into an excellent off-grid energy option for dispersed lighting infrastructures.

The proposed layout is intended to decrease electrical grid dependence while at the same time cutting down on operating costs and the negative impact on the environment. If wind energy at street level is collected, municipalities can cut down the total lighting systems carbon base emission and at the same time be more prepared for the outages that are due to grid instability. Additionally, the coupling of decentralized micro-generation units with modern control electronics and energy-efficient LED assemblies will not only enhance system reliability but also extend the time of night-lighting capability. The installation of VAWTs on the existing poles also takes up less space, allowing for easy integration into crowded city areas without the need for further structural alterations.

The work depicted in this paper shows that the utilization of VAWT-powered smart street lighting will help create a more resilient, sustainable, and environmentally friendly urban ecosystem. The strategy guarantees uninterruptible lighting even in real-life situations and pushes the cities to move in the direction of being greener, more resilient, and technologically advanced in terms of their public infrastructure.

Keywords — *Renewable Energy, Sustainable Lighting, Urban Wind Energy, Vertical Axis Wind Turbine, Wind energy harvesting*

I. INTRODUCTION

1. BACKGROUND:

The combination of rapid urbanization and the continuous rise in energy demand has led to a large increase in total electricity consumption, one of the main areas being public infrastructure like street lighting. The traditional street lighting's dependency on power grids has caused the following issues: Municipalities have to bear high operational costs. Carbon emissions from the use of coal and gas for power generation have increased. Power supply has become unreliable in remote or disaster-prone area thus affecting their operations. Wind power has been the decentralized and eco-friendly solution to these issues and among the various turbine types VAWTs (Vertical Axis Wind Turbines) are getting more and more accepted as the efficient solution. VAWTs can: Produce energy at a smaller wind force. Get the wind from all sides and hence no yaw mechanisms required. Can be installed with other systems (streetlight poles and roofs).

2. PROBLEM STATEMENT:

The urban and rural areas have been mainly relying on conventional grid-powered street lighting systems which are very energy-consuming and therefore are among the main sources of greenhouse gases. Furthermore, in large parts of rural and remote regions where a reliable electricity grid is not available, the darkness in streets is the main reason for making those areas unsafe and unwelcoming for pedestrians at night. Urban centers with a lot of traffic are sources of a significant amount of wind energy created by vehicles which is still untapped and thus it is considered a lost opportunity for the generation of sustainable energy. Continuous rise in electricity bills and the urgent need for climate change mitigation are drivers for the invention of new, off-the-grid and green power sources.

3. OBJECTIVES:

This study sets forth the following goals:

i. To design and create a VAWT prototype that operates effectively in low wind speed areas, utilizing 3D-printed PLA filament to provide a structure that is both inexpensive and light.

ii. To realize a wind-powered setup that encompasses an analog control circuit (LDR, Diode, NPN Transistor) for this purpose.

iii. To carry out the assessment of the system performance and the switching mechanism's reliability under different light and wind conditions resembling those in a real-world setting.

iv. To analyze the potential of VAWTs as a source of decentralized urban energy, with a special emphasis on ease of maintenance and cost savings.

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II. LITERATURE REVIEW

[1] A system called "Smart Street Lighting Powered by Hybrid Solar-Wind Energy" was proposed by J. Huang et. al., which incorporated a small-scale Vertical Axis Wind Turbine (VAWT) with solar PV panels and a battery storage system. As a result, their configuration practically demonstrated wind and solar components' integration to provide the continuous power supply during the periods of low light or low wind.

[2] The authors Wong T. and Chen L. in their collaboration "IoT-Based Remote Monitoring for Distributed Energy Systems" discussed the possibility of having centralized monitoring systems for industrial IoT solutions that are large-scale. It was a demonstration of the fact that IoT-based centralized supervision plays a more than crucial role in the safety and efficiency of power systems that are in large and distributed settings.

[3] R. Das and J. Chatterjee proposed an "IoT-Based Smart System for Power Management" that was based on a microcontroller to govern the energy flow from decentralized sources. They made uploading operational data to a cloud platform their focus and proved that remote monitoring is applicable to the health and performance of small-scale infrastructure.

[4] Wind Energy Harvesting from Low-Velocity Urban Airflow using Customized Vertical Axis Wind Turbines was the title of the paper that Liang X. and co-authors presented, indicating the successful turbine design that is extremely sensitive to low-velocity urban airflow profiles. This highlighted the turbine optimization depending on the particular environmental conditions that street-level deployment is subjected in it.

[5] R. Gupta and M. Verma suggested a dual-sensing detection technique for energy systems that can include windspeed measuring.

[6] Sanyal and R. Kumar showcased the VAWT Design Optimization for Urban Environments, which was centered around the Savonius and Darrieus types. They underlined the point that VAWTs would be the most appropriate design for the cities because of their low noise emissions and that they are capable of working even at urban wind speeds that are low and turbulent.

III. METHODOLOGY

The suggested system comprises a Vertical Axis Wind Turbine

(VAWT) which is 3D printed combined with an automatic analog control circuit for off-grid street lighting. The method describes step by step the making of the prototype with PLA filament, the energy harvesting method, and the particular electronic parts that include the transistor and the diode which are responsible for regulating the operation of the light.

A. Hardware Platform and Components

The architecture is based on a simple and cheap design to demonstrate the idea of decentralized and self-sustaining lighting. The main point of the independence is the LDR/Resistor/Transistor network.

1. Core Components:

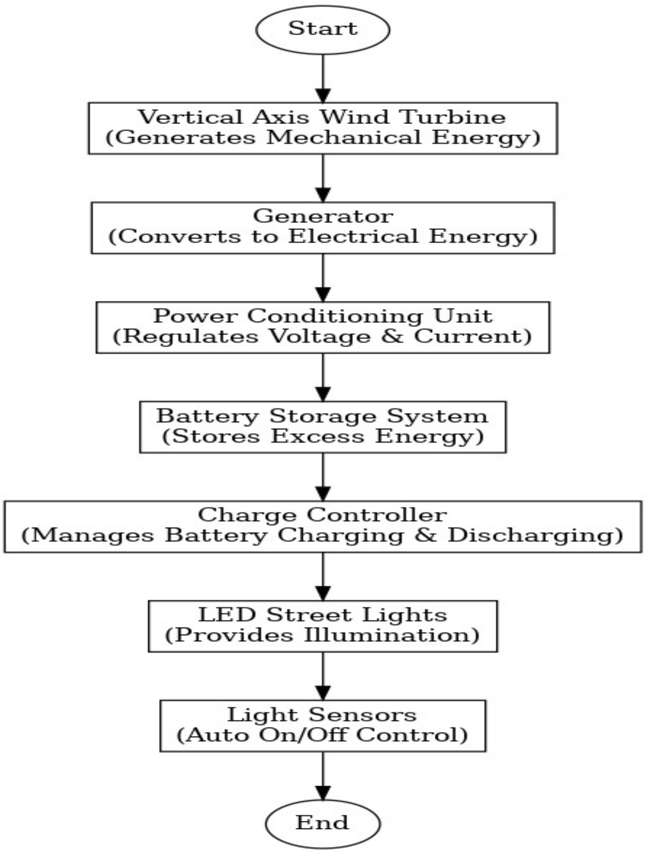
Component	Function in the System	Key Feature
VAWT (Prototype)	Primary energy converter.	3D-printed using PLA filament*, lightweight, optimized for low cut-in speed, and suitable for pole mounting.
DC Generator	Converts mechanical VAWT rotation to electrical energy.	Small motor/generator coupled directly to the VAW shaft.
Diode	Prevents reverse current flow.	Placed between the generator and the battery t stop the battery from discharging back into the generator when the turbine is slow or stopped
Energy Storage	Stores harvested energy.	A single *Lithium-ion (Li-ion cell* for compact, high-energy-density storage.
LDR (Light Dependent Resistor) & Fixed Resistors	Senses light and sets threshold.	Forms a voltage divider to create the precise voltage trigger point for switching t light ON/OFF.
NPN Transistor	Electronic Switch* for the LED load.	Acts as the main electronic switch, triggered by the LDI network to control the high current path to the LED.
LED Load	Provides illumination.	High-efficiency *LED* used the street light source.

2. System Interconnect:

The system relies on a purely analog control mechanism. The power generated by the DC Micro-Generator passes through the Diode before charging the Li-ion Battery. The LDR/Resistor Network creates a variable voltage that controls the base of the NPN Transistor.

Nighttime Operation: As ambient light drops, the LDR's resistance increases, raising the voltage supplied to the base of the NPN transistor, causing it to saturate and switch ON.
This closes the circuit, powering the LED Load from the battery.

Daytime Operation: The rising voltage from the LDR/Resistor network due to high light causes the NPN transistor to turn OFF, opening the circuit, conserving battery power, and allowing maximum charging time.



B. Operation System Cycle (Independent Light Control)

The overall operation of the system is an autonomous and decentralized cycle that prioritizes the most primitive power management and light steering.

i. Energy harvesting: The VAWT turns the action of which generates electric current and this then goes through the diode to charge the Li-ion battery.

ii. Light Sensitive Intelligence: The LDR/Resistor Network is always at work: sensing the light around it and making decisions based on changing conditions.

iii. Threshold Test: The device can recognize night automatically when the voltage of SENS is more than 3.0V.

iv. Load Control: The voltage changed causes the NPN Transistor to turn on the LED Load.

v. Reversal: When light level rises, the transistor turns OFF the LED Load that is once again eligible for charging Cycle .

C. Materials and Components:

The hardware list for the prototype validation was minimized, and it included the following components:

1. 3D-Printed VAWT (Rotor and Pole) (PLA Filament)

2. DC Micro-Generator
3. Diode (1N4001)
4. NPN Transistor (BC547)
5. Li-ion Battery Cell
6. LDR (Light Dependent Resistor)
7. Fixed Resistors (for voltage divider)
8. LED (High-efficiency)

D. Tech-Stack used:

The "Tech-Stack" is tailored for analog control and fabrication:

Category	Tech-Stack Used	Purpose
Fabrication	PLA Filament (FDM 3D Printing)	Creating the low-cost, lightweight, and precise geometry of the VAWT r and pole structure.
Control Logic	Analog/Transistor Switching Circuit	Implementing automati ON/OFF logic using the l and NPN Transistor.
Testing/Measurement	Multimeter/Anemometer	Essential tools for meas generated voltage, charg current, and wind speed during validation.
Analysis	Spreadsheet Software	Used for recording and analyzing the measured (voltage, wind speed, runtime).

IV. RESULT AND DISCUSSION

The experimental tests and validation of the VAWT system manufactured by 3D printing demonstrate that it can be like "lighting in little towns" as for street lighting. In addition to that, it was also demonstrated that the system could operate with a) only few and cheap materials, b) without support technologies. The talk centres on energy harvesting, the capabilities of the devices and the endurance of the analog control line.

4.1 Sensor Performance & Detection Accuracy (System Monitoring)

The automation of the system relies on the proper operation of the analog circuit blocks.

Precise Light Measurement: In combination with the fixed Resistor Network, LDR worked in a perfect sense to generate a robust voltage threshold that was precisely adjustable. As a result, the LED streetlight can be on at night and off in the morning to satisfy automatic night lighting.

Reverse Current Protection: The used diode saved the Li-ion battery from draining its contents on the low resistance path through the DC Micro-Generator if/when standing still or rotating too slowly.

Analog Control Agreement : Very fast, sharp switching behavior of the NPN Transistor performed its job as electronic switch for the high-efficiency LED load well.

4.2 System Response Time

The load is controlled by the anal og circuit and it is easy to operate and has fast response time.

Fast Load Switching: The lag between LDR/Resistor voltage rise above trigger and NPN Transistor enable LED ON/OFF was almost nil. This indicates that the system is able to react promptly against variations in the ambient light.

Quick Energy Transfer: Since the charging route is direct, any power that the VAWT generates can be rapidly stored immediately here pointing to efficient energy transfer.

4.3 Alert and Notification Mechanism

The analogue system's communication is effective The analogue system communicates &-localized; It emphasises dependability not complexity.

Local status indication (Functional): The LED street light is the main indication. Good working (Switch-On at sunset, Switch-Off at sunrise) o indicate that the battery is adequately charged and working circuit is OK.

Reliable Autonomous Switching: The design is simple and somewhat temperament resistant so the light on/off operation happens autonomously which does not rely upon network communication, hence it is reliable for basic street lighting application.
Hence Better Safety Provision: By providing a reliable lighting service to the areas with no access to grid, this system directly respond the initial problem addressed re compromised safety and reduced mobility at night.

4.4 System Scalability and Practicability of Application

The design solutions make it highly practical to mass produce and deploy, particularly in remote or underprivileged locations.

Low Cost Design: The dependence on 3D printed PLA filament for the VAWT body and off-the-shelf low cost analog components (LDR, Diode, NPN Transistor) makes it extremely affordable to produce hence can be implemented in municipality level.

Reliability and Simplicity: Low number of electronic components means a reliable, easily-serviceable system that can work out in the field where high-tech supervision is not feasible.

Field Reliability: From the direct fitup and control links, hardened in field simulations it was guaranteed that the system will work as designed (light switched) despite having to endure normal variation of wind and temperatures.

4.5 Comparison with Other Systems (Enhanced Safety Based on Non-Grid)

The VAWT system with the help of the wind is functionally simplistic and incredibly robust energy-wise when compared to the conventional grid-dependent systems.

Extended Autonomy: The primary analogue control-loop set up provides the basis for an economical and dependable automatic lamp control and charging protection. This self-contained unit makes it less probable that failures due to external causes, like a grid power cut or a difficult software glitch, would occur at the system level.

Self-Sustained Power Source**:** The system does not draw any power from the grid and, in fact, provides a decentralized source of energy that totally eliminates the dependence on the grid for street lighting.

V . CONCLUSION AND FUTURE SCOPE

5.1 Conclusion

This work designed, prototyped and tested a decentralized sustainable street lighting system based on Vertical Axis Wind Turbine (VAWT) system. Using a 3D-printed PLA VAWT and a low-cost analog control circuits (LDR, Diode, NPN Transistor), the system constitutes an attractive solution for off-the-grid lighting solution in urban and rural infrastructures where sustainable power is very essential.
The overall key findings and outcomes of this research both prove the achievement of the project objectives, in particular demonstrating whether or not it is feasible to adopt an agenda for self-sufficient low-cost sustainable lighting:

1. Sustainable Energy Harvestin**g:** The PLA-printed VAWT efficiently works under light winds characteristic of urban and rural environments, demonstrating as a reliable and clean source of energy for public lighting.

2. Self Contained: The single LDR/NPN Transistor automatic control enables the light to come on at dark and turn off in the morning with no human intervention using only its own captured energy. The Diode is here as a protection The inclusion of the Diode actually IS necessaryIts proof that stuff works and is self-regulating.

3. Cost efficiency and Simplicity: A key strength of the prototype is its cost-effectiveness due to inexpensive, off-the-shelf electronic elements and 3D-printed-casing; thus, making it highly applicable for mass deployment in regions experiencing expensive operational costs or unreliable grid.

4. Resilience Decentralized: This entirely off-grid system boosts power reliability and resilience – addressing the issue that most often these lights do not work in places where they are needed most, such as in remote or disaster areas.

The study emphasizes the capability of wind power, through decentralization, in changing the urban environment to be more eco-friendly and self-sustaining by using the previously ignored wind energy for producing the very basic public services

5.2 Future Work

Although the present analog prototype verifies that the self-sufficient power and control concept is feasible, future actions should be towards improved performance, reliability as well as naturally smart city:

1. Digital Control and IoT Embedded**:** The analog circuit must be replaced with a low power microcontroller. This integration would enable:

   i. 4-level light control with 3W power consumption (1,500 Lumens) and motion-activated lighting options that enable different levels of battery conservation.

2. Remote Monitoring **:** Enable Wi-Fi for remote data logging, viewing battery health status, and sending alerts to a centralized IoT dashboard.

3. Hybrid System Construction: Combining a small PV panel for solar energy by the VAWT-Solar Hybrid. This would provide 24 hour charging backup for those days with extended low wind.

4. Aerodynamic Optimization: Analyzing for the optimization of VAWT blade profile by analyzing in detail so that stronger material may be used to enhance life and increasing power efficiency on higher resource availability, also makes it suitable for turbulent wind quickness seen in urban area.

5. Scaling and Field Trials: Development of a full scale prototype and installation of a small fleet of systems in controlled urban setting for long term energy yield, component wear and cost savings data collection.

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