

Fabrication of a 3D-Printed Horizontal Windmill for Electricity Generation and Water Pumping

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Abstract: This study investigates the design, fabrication, and performance of a small-scale horizontal-axis windmill integrated with dual-purpose functionality: electricity generation and water pumping. By leveraging renewable wind energy, the system captures kinetic energy through a 3D-printed aerodynamic rotor and converts it into mechanical energy, which is subsequently transformed into regulated electrical power. The system incorporates an energy storage and conditioning unit to ensure continuous operation under fluctuating wind conditions. The stored energy is utilized to drive a diaphragm pump for water lifting, while simultaneously providing the regulated electrical supply for external loads. The proposed system demonstrates a cost-effective, decentralized energy solution tailored for rural and off-grid regions where access to conventional power and water infrastructure is limited. Experimental evaluations confirm the feasibility of the integrated architecture, achieving stable power conversion and reliable water pumping performance. The study underscores the significance of modern fabrication techniques, such as 3D printing, in enhancing the modularity, accessibility, and scalability of small-scale renewable energy systems. The results provide a practical demonstration of how small-scale renewable infrastructure can contribute to sustainable development and resource management in resource-constrained areas.

Index Terms: Wind Energy, 3D Printing, Renewable Energy, Electricity Generation, Water Pumping, Horizontal Axis Wind-mill, Decentralized Energy.

I. INTRODUCTION

The global demand for energy has escalated due to rapid population growth, industrial expansion, and agricultural intensification. Conventional energy resources, primarily fossil fuels like coal, oil, and natural gas, are being depleted at an alarming rate while contributing to significant environmental challenges, including greenhouse gas emissions and global climate change. Simultaneously, many rural and remote areas, particularly in developing nations, lack consistent access to reliable electricity and clean water. These regions often depend on expensive and polluting diesel-powered generators or manual labor for energy and water extraction. Consequently, there is an urgent requirement for sustainable, decentralized, and renewable energy solutions that can address these fundamental infrastructure needs efficiently.

Wind energy has emerged as a premier candidate for renewable energy production due to its abundance, cleanliness, and cost-effectiveness. Historically, wind power was harnessed for mechanical tasks like grain milling and water pumping. Modern advancements have shifted the focus toward large-scale electricity generation; however, the potential for small-scale, multipurpose wind energy systems remains an essential research frontier. Small-scale wind turbines offer a versatile platform for decentralized applications, particularly when integrated with modern fabrication techniques and efficient energy management systems.

This project focuses on the development of a 3D-printed horizontal-axis windmill capable of simultaneous electricity generation and water pumping. The integration of dual functions within a single framework optimizes energy utilization and reduces the need for separate infrastructures. The system is designed to operate under variable wind conditions, employing energy storage to bridge the gap during periods of low wind availability. This approach not only provides a clean alternative to fossil fuels but also offers a scalable model for self-sustaining infrastructure in off-grid environments.

A. Objectives of The Project

The primary goal of this research is to develop a practical, renewable energy solution that addresses energy and water need simultaneously. The specific objectives include:

- **Efficient Energy Conversion:** To convert wind energy into mechanical energy and subsequently into usable electrical energy with minimal losses.

- **Energy Storage and Regulation:** To ensure continuous operation by storing generated energy and regulating power output under variable wind conditions.
- **Support for Rural Applications:** To provide a practical solution for rural and off-grid areas where conventional power supply is unreliable or unavailable.
- **Cost-Effective Design:** To fabricate a low-cost and simple system using easily available materials and modern fabrication techniques like 3D printing.
- **Environmental Protection:** To reduce carbon emissions and environmental pollution by minimizing reliance on fossil fuels.
- **Educational and Practical Value:** To develop a working model that demonstrates the principles of renewable energy conversion and sustainable engineering design.

B. Scope of The Project

The scope of this project is multi-dimensional, covering technical, environmental, and socio-economic aspects:

- **Wind-Based Energy System:** The project utilizes wind energy as the primary source of power, making it suitable for regions with adequate wind availability.
- **Electricity Generation and Water Pumping:** The system supports dual applications, enabling both electrical power generation and water pumping from a single setup.
- **Energy Storage Capability:** Generated energy can be stored and used during low wind conditions, improving reliability and usability.
- **Small-Scale and Decentralized Application:** The system is suitable for domestic use, small Agricultural fields, and educational demonstrations.
- **Eco-Friendly Operation:** The project promotes clean energy usage and contributes to reducing environmental pollution and energy wastage.
- **Scalability:** The design can be further enhanced or scaled up for higher power output and larger applications.
- **Sustainable Development Contribution:** The project supports sustainable development goals by addressing energy and water needs through renewable resources.

II. LITERATURE REVIEW

The shift toward renewable energy has prompted extensive research into small-scale wind energy conversion systems (WECS). Small wind turbines are particularly suited for rural electrification and decentralized power due to their low operating costs and minimal environmental footprint.

A. Small-Scale Wind Energy Systems

Research by Manwell et al. highlighted that horizontal-axis wind turbines (HAWTs) typically provide higher aerodynamic efficiency and better energy capture than vertical-axis designs under moderate wind conditions. Their study concluded that horizontal-axis wind turbines provide better performance across various wind speeds, which is essential for maximizing yield in small-scale setups. Burton et al. analysed the performance and design considerations of small wind turbines, emphasizing the need for robust electromechanical processes for converting mechanical rotation into electrical energy. Their research underlined the importance of handling the intermittent nature of wind through effective power conditioning and energy storage solutions. Similarly, Mathew discussed the resource analysis and economic feasibility of wind energy, noting that small-scale deployment is often more viable for immediate rural needs than large grid extensions.

B. Integrated Energy Applications

The integration of multiple applications into a single wind-based setup has been a focus of recent literature. Fraenkel studied traditional and modern wind-powered water pumping systems, noting their effectiveness in remote areas lacking grid connectivity. Khan et al. compared wind-powered pumps with diesel-powered alternatives, reporting significant reductions in operational costs and environmental impact. Kumar et al. further demonstrated hybrid systems that simultaneously provide electrical power and water pumping, showing improved overall system efficiency compared to standalone units. Their findings suggest that utilizing wind energy for multiple purposes within a single platform can optimize the utility of the captured wind resource and improve the overall return on investment for small-scale energy systems.

C. Role of 3D Printing in Renewable Energy

Modern fabrication techniques, specifically 3D printing (additive manufacturing), have revolutionized the prototyping and production of wind turbine components. Rao et al. (2021) observed that 3D printing significantly reduces manufacturing costs and enables the rapid prototyping of complex aerodynamic structures like turbine blades. They

highlighted the advantages of additive manufacturing in enabling decentralized production and customization of turbine parts to suit local wind regimes. The ability to customize air foil profiles and maintain lightweight characteristics makes 3D printing an ideal choice for developing cost-effective and modular windmill systems for decentralized use. This technological shift allows for the democratization of renewable energy infrastructure fabrication.

D. Problem Statement and Proposed Solution

Existing systems for electricity generation and water pumping primarily rely on conventional energy sources like grid electricity and diesel engines. These methods face several challenges, including high dependency on non-renewable energy sources, high fuel and electricity costs, and frequent power cuts in rural areas. Furthermore, using separate systems for power generation and water pumping often leads to inefficient energy utilization. To address these gaps, the proposed system utilizes a single windmill-based framework for dual-purpose operation, integrating energy conversion, storage, and utilization into a single functional unit. This holistic approach ensures that wind energy is harnessed and applied in a manner that maximizes its socio-economic impact.

III. METHODOLOGY AND DETAILED MATERIALS ANALYSIS

The methodology for this project involves the selection, analysis, and integration of specialized mechanical and electrical components to create a functional renewable energy platform.

A. 3D-Printed Windmill Fabrication

The significance of 3D printing in this context lies in the ability to prototype rapidly, iterate on blade profiles, and reduce the overall manufacturing complexity. By using additive manufacturing, the structural integrity of the blades can be optimized while keeping the weight low, which reduces the cut-in wind speed and enhances the starting torque of the turbine.



B. Component Analysis and Specifications

The system's performance is highly dependent on the characteristics of its core components, which are analysed in detail below.

1) 500RPM DC Motor (Generator):

A 500RPM brushed DC motor is utilized as the electromechanical generator. This motor is selected for its high-speed performance and moderate torque delivery.

- **About the Motor:** The 500RPM DC motor is a high-speed electric motor commonly used in projects requiring fast rotational motion. It delivers rapid rotation while maintaining reasonable energy efficiency.
- **Specifications:**
 - Speed: 500 RPM
 - Operating Voltage: 6V - 12V DC
 - Current Consumption: 300mA – 1.2A

- Torque Output: 2-5 kgf.cm
- Weight: 150g-300g
- Motor Type: Brushed DC Motor
- Shaft Diameter: 5mm – 6mm

- **Advantages:** High speed performance, compact and lightweight, energy efficient, easy to control, and cost-effective.

2) *12V, 1.2Ah Rechargeable Battery:* A Sealed Lead-Acid (SLA) or Valve-Regulated Lead-Acid (VRLA) battery is used for energy storage.

About the Battery: This rechargeable sealed energy storage device is commonly used in backup power systems and small automation projects. Its sealed construction makes it spill-proof and suitable for indoor and portable applications.



- **Working Principle:** The battery operates through an electrochemical process where lead dioxide (positive plate) and sponge lead (negative plate) react with the electrolyte (sulfuric acid). This reversible reaction produces electrons, generating a 12V DC supply.
- **Specifications:**
 - Nominal Voltage: 12 Volts
 - Capacity: 1.2 Ah
 - Charging Voltage: 13.5V - 14.5V
 - Cycle Life: 300-500 cycles
 - Operating Temperature: -15°C to + 50°C

3) *Diaphragm Pump:* A positive displacement diaphragm pump (membrane pump) is used for the water pumping application.



- **About the Pump:** The diaphragm pump uses a flexible diaphragm to move fluids. It is widely used for handling liquids and slurries due to its leak-free operation and chemical resistance.
- **Specifications:**
 - Flow Rate: 3 L/min
 - Voltage: 12V to 480V DC
 - Current: 0.1-10 A
 - Motor Speed: 100-3600 RPM

4) *Inverter Circuit Board:* An inverter circuit board transforms DC power from the battery into AC power

- **About the Inverter:** This component is designed to transform direct current (DC) into alternating current (AC). It is a key component in power conversion systems.
- **Specifications:**
 - Efficiency: 85% to 98%

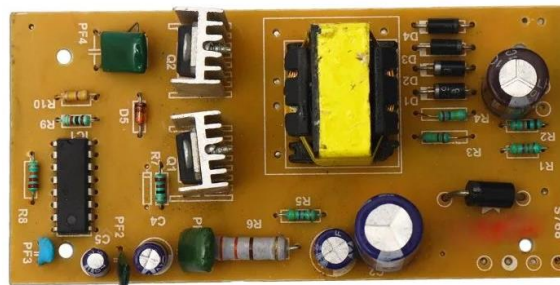
- Output Voltage: 120V AC or 230V AC
- Output Frequency: 50Hz 60Hz
- Switching Frequency: 20KHz to 100kHz

IV. SYSTEM ARCHITECTURE AND OPERATIONAL LOGIC

The system's architecture is meticulously designed to ensure seamless coordination between energy capture, conversion, storage, and utilization.

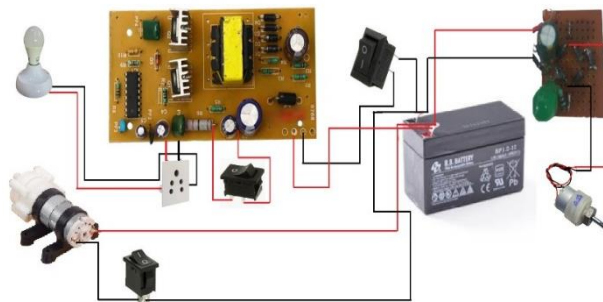
A. Functional Units

The architecture is divided into four primary functional units: 1) **Energy Capture Unit**: Extracts kinetic energy from moving air using the 3D-printed horizontal-axis windmill. The aerodynamic blades are designed to rotate under moderate wind speeds, converting natural wind flow into rotational mechanical motion. 2) **Energy Conversion Unit**: Transforms the rotational mechanical motion into electrical energy using the DC motor in generator mode. 3) **Energy Storage and Regulation Unit**: Manages the generated power. A charging circuit conditions the energy and stores it in the 12V battery. 4) **Utilization Unit**: Applies the regulated energy for two simultaneous outputs: providing electrical power supply and operating the diaphragm pump for water lifting.



B. Detailed Working Principle

The system operates on the principle of renewable energy conversion. When wind flows across the 3D-printed blades, it generates lift and drag forces that cause the rotor to spin, converting wind kinetic energy into mechanical torque. This torque drives the generator, which produces electrical energy. Because wind speed is naturally variable, the electrical energy is conditioned and stored in the battery.



The stored energy is then regulated to meet operational requirements and supplied to the load system. Part of the energy provides electrical output for external loads, while the remaining portion drives the diaphragm pump to lift water for domestic or agricultural use.

V. SIGNIFICANCE OF 3D PRINTING IN WINDMILL FABRICATION

The application of 3D printing in this project goes beyond prototyping; it is a fundamental driver for the system's viability in decentralized contexts.

A. Aerodynamic Optimization through Rapid Prototyping

One of the primary advantages of 3D printing is the ability to fabricate complex, high-precision aerodynamic shapes that would be difficult or costly to produce using traditional subtractive manufacturing or molding techniques. 3D printing allowed for the rapid fabrication and testing of multiple blade designs, enabling an iterative optimization process to find the most efficient geometry for low-to-moderate wind regimes.

B. Material and Cost Efficiency

3D printing minimizes material waste by only using the necessary amount of plastic filament to build the part layer by layer. Furthermore, the accessibility of desktop 3D printers means that replacement parts can be manufactured locally, reducing the lead time and logistical costs associated with maintenance in remote regions

VI. RESULTS AND DISCUSSION

The fabricated system was subjected to experimental testing to evaluate its operational performance and reliability.

A. Performance Analysis of Energy Capture and Conversion

The windmill demonstrated consistent rotational motion under moderate airflow. The 3D-printed blades successfully captured wind energy and translated it into mechanical rotation with minimal vibration and loss. The horizontal-axis configuration enabled efficient aerodynamic performance, allowing the system to operate even under variable wind speeds.

B. Evaluation of Storage and Pumping Functions

The energy storage mechanism functioned effectively, allowing the system to bridge periods of low wind availability. The regulated output from the battery maintained stable functionality for both the electrical supply and the water pumping mechanism. The diaphragm pump performed reliably, achieving the target flow rate for water lifting.

C. System Integration Analysis

The integration of energy capture, conversion, storage, and utilization into a single framework was found to be efficient and practical. The coordinated operation of all subsystems ensured smooth performance without significant losses or instability. The compact and modular structure contributed to ease of operation and maintenance.

VII. CONCLUSION

The 3D-printed horizontal windmill project successfully demonstrates an integrated, sustainable solution for decentralized energy and water needs. By combining energy capture, conversion, storage, and dual-purpose utilization into a single functional framework, the system offers a reliable and eco-friendly alternative to conventional power sources. The use of 3D printing for the fabrication of the windmill components underscores its significance in making renewable energy technologies more accessible, modular, and cost-effective. The experimental results validate the system's performance, proving its viability for deployment in rural and off-grid regions.

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