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Design of Horizontal Axis Wind Turbine for Power Generation

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Abstract—

The growing global emphasis on renewable energy sources has accelerated the development of efficient and sustainable wind energy systems. This project presents the design of a **Horizontal Axis Wind Turbine (HAWT)** aimed at small-scale power generation. The primary objective is to develop an optimized turbine model capable of harnessing wind energy effectively for electricity production in low to moderate wind conditions.

Advanced computer-aided design (CAD) techniques were utilized to model and simulate the wind turbine using **Siemens NX CAD software**. The software enabled precise 3D modeling of turbine components, including the rotor blades, hub, nacelle, and tower, ensuring accurate geometry and aerodynamic performance. Special focus was given to blade profile design and orientation to maximize efficiency and torque generation.

The design process considered key parameters such as wind speed, blade length, material selection, and rotational speed. Simulation and analysis were conducted to evaluate the mechanical behavior and energy output potential of the system under various operational conditions. The results demonstrate that the proposed design can effectively contribute to clean and sustainable power generation, with potential applications in rural and off-grid areas.

Key words: WIND TURBINE,NX CAD SOFTWARE.

I. INTRODUCTION

Wind turbines are devices that convert the kinetic energy of the wind into electrical energy. They work on a simple principle: instead of using electricity to make wind (like a fan), wind turbines use wind to make electricity.

1.1 Here's a basic introduction to wind turbines:

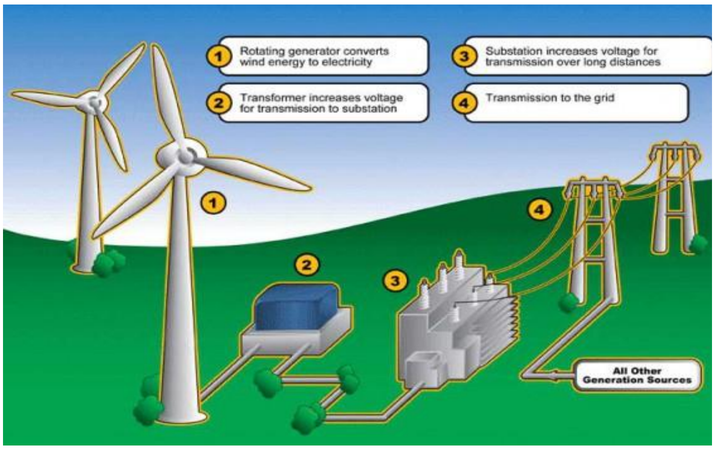
Wind Capture: The wind flows across the turbine's blades, which are shaped like airplane wings. This creates a difference in air pressure between the two sides of the blade.

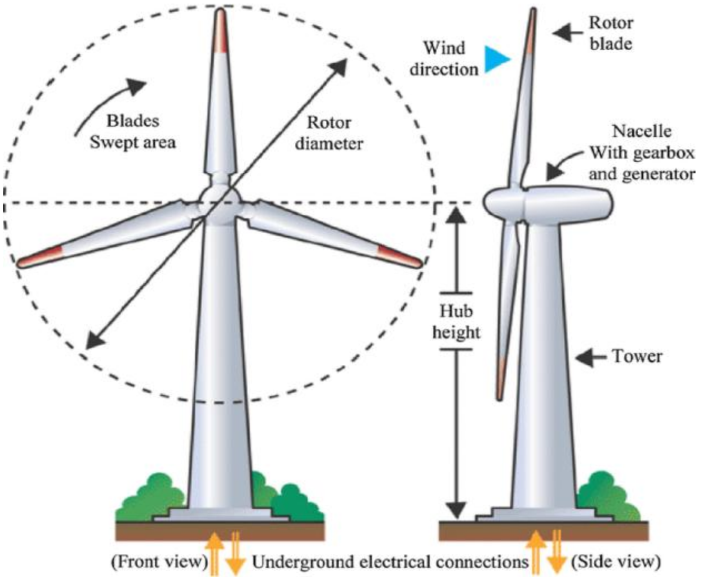
Rotation: The difference in pressure generates lift, causing the blades to rotate.

Mechanical Energy Conversion: The rotating blades are connected to a central shaft, which in turn is connected to a gearbox (in most utility-scale turbines). The gearbox increases the rotational speed of the shaft.

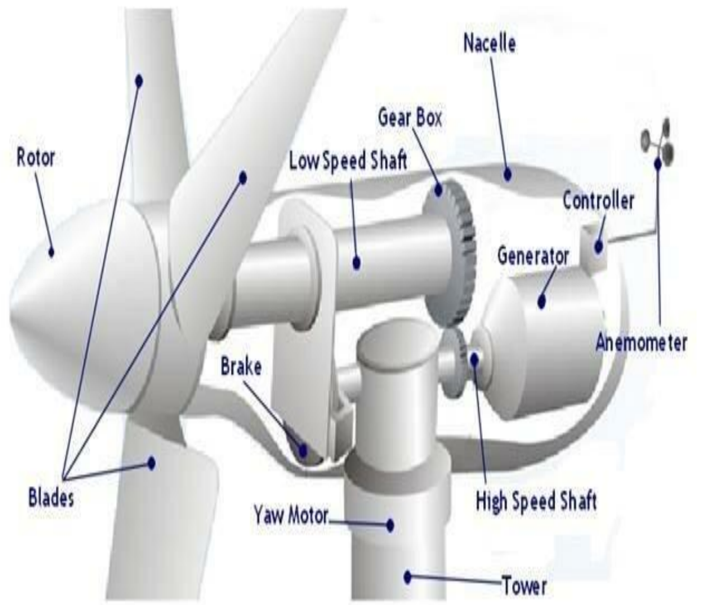
Electricity Generation: The high-speed shaft is connected to an electric generator. As the shaft spins the generator, it converts the rotational mechanical energy into electrical energy through electromagnetic induction.

Power Transmission: The electricity produced is then typically fed into the electrical grid via transformers and transmission lines to be distributed to homes, businesses.





Key Components of a Wind Turbine:



Rotor Blades: These are the large, aerodynamic surfaces that capture the wind's energy. Most modern turbines have three blades.

Nacelle: This is the housing located at the top of the tower that contains the gearbox, generator, control systems, and other components.

Tower: The tall structure that supports the nacelle and rotor. The height allows the blades to access stronger and more consistent winds.

Hub: The central part of the rotor where the blades are attached.

Gearbox (most large turbines): Increases the rotational speed from the low-speed rotor shaft to the high-speed generator shaft.

Generator: Converts the mechanical rotational energy into electrical energy.

Control System: Monitors wind speed and direction, adjusts the blade pitch, and controls the turbine's operation for safety and efficiency.

Yaw System (for horizontal-axis turbines): Rotates the nacelle to keep the rotor facing optimally into the wind.

Example uses for waste heat include generating electricity, preheating combustion air, preheating furnace loads, absorption cooling, and space heating. A heat exchanger is a device which is used to transfer heat from a hot body to a cold body. That lot waste heat is recovered and conversion into useful electricity using Thermo electric generator and converting cooling effect.

DESIGN

NX CAD (Computer-Aided Design), formerly known as Uni graphics, is a powerful and comprehensive software solution developed by Siemens Digital Industries Software. It is a high-end CAD/CAM/CAE (Computer-Aided Manufacturing/Computer-Aided Engineering) system widely used across various industries for product design, engineering, and manufacturing.

Key Capabilities and Features:

3D Modeling: NX CAD offers robust tools for creating and modifying complex 3D geometries. It supports various modeling techniques, including:

Parametric Modeling: Design based on dimensions and relationships, allowing for easy modification and design iterations.

Direct Modeling: Enables quick and intuitive geometry manipulation without relying on the model's history.

Surface Modeling: Advanced tools for creating and editing complex freeform surfaces, including Class A surfaces for high aesthetic requirements.

Solid Modeling: Creation of solid models with precise volumetric information.

Synchronous Technology: A unique Siemens feature that combines the speed and flexibility of direct modeling with the control of parametric design.

Sheet Metal Design: Dedicated tools for creating and unfolding sheet metal parts, considering manufacturing constraints.

Assembly Modeling: Tools for efficiently creating and managing large and complex product assemblies, including top-down and bottom-up design approaches.

Drafting and Documentation: NX CAD facilitates the creation of detailed 2D drawings from 3D models, including:

Automatic view generation (orthographic, isometric, auxiliary, etc.).

Comprehensive annotation tools (dimensions, tolerances, notes, symbols).

Compliance with international drafting standards.

Model-Based Definition (MBD): Embedding product and manufacturing information directly into the 3D model, reducing the reliance on 2D drawings.

Simulation and Analysis (CAE Integration): While NX CAD primarily focuses on design, it tightly integrates with NX CAE for various simulation and analysis tasks, such as:

Finite Element Analysis (FEA) for stress, thermal, and vibration analysis.

Computational Fluid Dynamics (CFD) for fluid flow and heat transfer simulations.

Kinematics and dynamics analysis for studying the motion of mechanisms.

Manufacturing (CAM Integration): NX CAD seamlessly integrates with NX CAM to provide a complete design-to-manufacturing solution, including:

Numerical Control (NC) programming for CNC machine tools.

Toolpath generation for various machining operations (milling, turning, drilling, etc.).

Simulation and verification of machining processes.

Support for additive manufacturing (3D printing).

Industrial Design and Styling: NX offers advanced tools for industrial designers to create aesthetically pleasing and ergonomic product shapes, including:

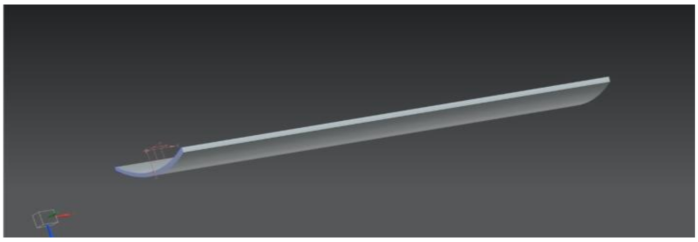
Freeform modeling and sculpting

DESIGN STEPS OF A WIND TURBINE BLADE USING NX CAD

Designing a wind turbine blade in Siemens NX CAD involves 3D modeling, aerodynamics analysis, and structural validation. Below is a step-by-step guide for creating a wind turbine blade from scratch.

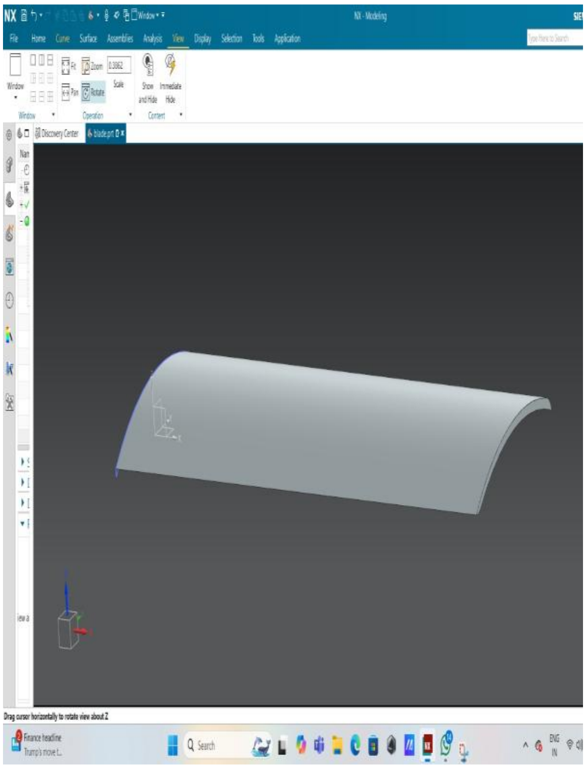
A. Step 1: Define Design Requirements & Parameters

- Before starting the design, determine:
 Blade Length & Shape – Typically **30m to 100m**, depending on wind conditions.
 Airfoil Profile – Choose from standard profiles like **NACA 4412, DU Series, or S Series**.
 Material Selection – Usually **fiberglass, carbon fiber, or composites**.
 Twist Angle & Tapering – Ensures optimal aerodynamic efficiency.
 Number of Blades – Typically **3 blades** for utility-scale turbines.



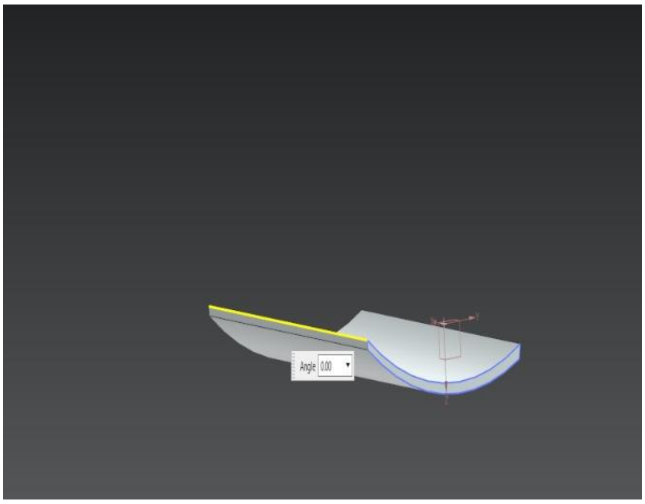
B. Step 2: Create the Blade Airfoil Profile

1. **Start NX CAD and Open a New Part**
   - Go to **File → New → Model**.
2. **Import or Sketch Airfoil Section**
   - Use **Curve Tool → Spline** to manually sketch or import **NACA airfoil data** using .csv or .txt.
   - Adjust **leading-edge radius** and **trailing-edge sharpness**.
3. **Define Multiple Airfoil Sections**
   - Create sections at different **blade span locations** (root, mid, tip).
   - Modify **chord length and thickness** for aerodynamic efficiency.



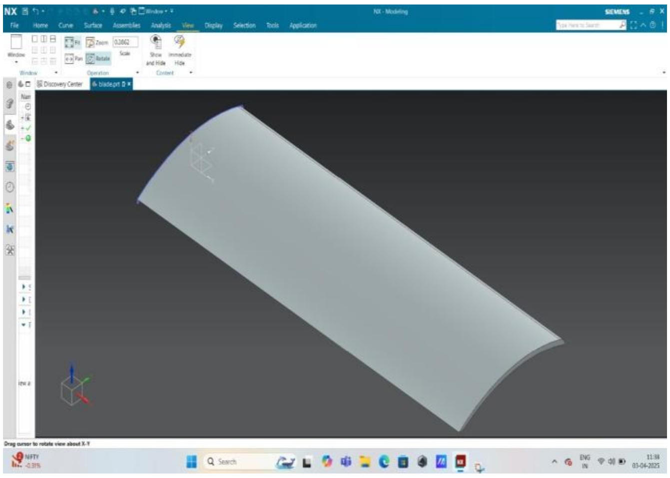
C. Step 3: Loft the Blade Shape (Surface Modeling)

1. **Use the "Through Curve Mesh" or "Swept Surface" Command**
   - Select multiple **airfoil profiles** and generate a **lofted surface**.
2. **Apply Twist & Taper**
   - Adjust **twist angles** (e.g., **10° at root, 0° at tip**) using the **rotation tool**.
   - Taper the blade width from **wide at the root to narrow at the tip**.
3. **Create the Blade Tip & Root Connection**
   - Use the **"Blend" tool** to create a **smooth transition** at the tip.
   - Model a **circular root hub connection** for attachment to the rotor.



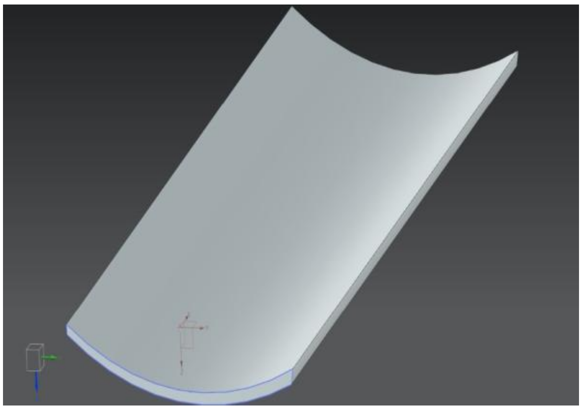
D. Step 4: Convert to Solid Model

1. **Use the "Thicken" Tool**
   - Convert the surface model into a **solid structure**.
2. **Apply Structural Reinforcements**
   - Use **rib and spar structures** for added strength.
3. **Create Cutouts for Weight Reduction**
   - Design **internal hollow sections** to minimize weight.



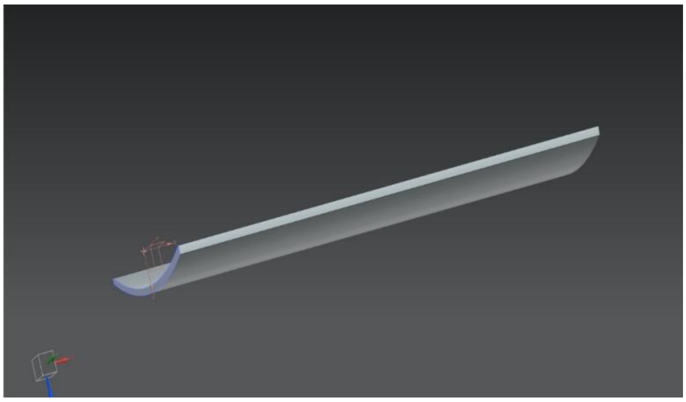
E. Step 5: Structural & Aerodynamic Analysis

1. **Use NX CAE for Structural Analysis**
   - Apply **material properties** (fiberglass, carbon fiber).
   - Run **Finite Element Analysis (FEA)** to check stress and deformation.
2. **Aerodynamic Simulation in NX Flow**
   - Perform **CFD analysis** to optimize airflow and lift efficiency.



F. Step 6: Final Adjustments & Optimization

1. **Modify Geometry**
   - Adjust thickness, curvature, and weight distribution for efficiency.
2. **Apply Surface Finishing & Texture**
   - Define **coatings** for durability and weather resistance.
3. **Create Technical Drawings**
   - Use **Drafting Tools** for **2D manufacturing drawings and annotations**.



G. Step 7: Export & Manufacturing Preparation

1. **Export 3D Model**
   - Save in **STEP, IGES, or STL format** for manufacturing.
2. **Prepare for CNC Machining or 3D Printing**
   - Generate **tool paths** using **NX CAM** for automated production.
3. **Documentation & BOM**

- Create a **Bill of Materials (BOM)** with material specifications.

DESIGN DATA FOR 200 WATTS HORIZONTAL AXIS

Kinetic energy K.E = $1/2mv^2$

Mechanical power P = ½ ρAV^3 =1/2 *1.229*2.364*5^3

Average air density ρ = 1.229 kg/m^3

Area swept by the rotor blades A= πr^2

Radius of the rotation of the blade = 0.89408 m

A= $\pi(0.89408)^2$

A= 2.5113 m^2

Radius of small ring of the rotor r_1 = 0.2159m

Area of small ring of rotor a = πr_1^2

= $\pi(0.2159)^2$

= 0.1464m

Total area swept by the blades = A-a

=2.5113-0.1464

=2.364m^2

Average velocity of cut in wind V_i = 5 m/s

Average velocity of cut out wind V_O=25 m/s

Mechanical power P=1/2 *1.229*2.364*5^3

P=181.58 watts

Calculating mechanical power for various wind velocities range 3 to 6 m/s

P=1/2 *1.229*2.364*3^3

=39.22watts

P=1/2 *1.229*2.364*4^3

= 92.97 watts

P=1/2 *1.229*2.364*6^3

=313.77 watts

Available power = Mechanical power

=1/2 ρAV^3

P = 181.58 watts

P=1/2 *1.229*2.364*7^3

P = 498.26 watts

P=1/2 *1.229*2.364*8^3

P = 743.77 watts

P=1/2 *1.229*2.364*9^3

P = 1059 watts

Actual power P = V*I watts

V= Voltage in volts

I = Current in amps

P = 20*5

= 100 watts

The efficiency ‘η’ or more commonly called as the power coefficient(Cp)

Actual power delivered divided by the available power

η= (actual power/available power)*100

= (100/181.58)*100

η = 55.07%

η= (actual power/available power)*100

= (100/313.77)*100

η = 31.87%

η = (actual power/available power)*100

= (100/498.26)*100

η = 20.06%

η = (actual power/available power)*100

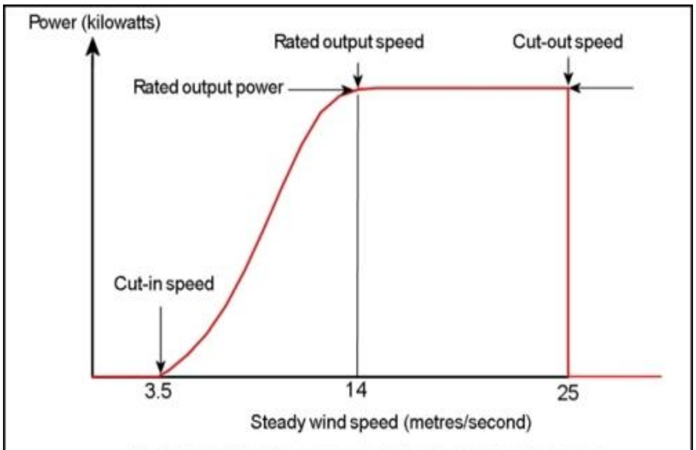
= (100/743.77)*100

$\eta = 13.44\%$

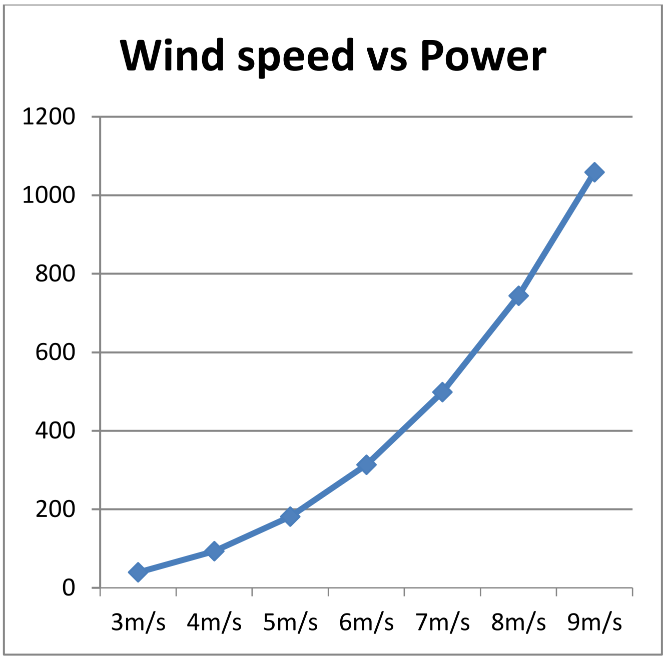
4.3 TABLE FOR VARIOUS WIND SPEED AND POWER

SNO	WIND SPEED(m/s)	AVAILABLE POWER(watts)
1	3	39.22
2	4	92.97
3	5	181.58
4	6	313.77
5	7	498.26
6	8	743.77
7	9	1059

4.4 Model graph for various wind speed and available power



Typical wind turbine power output with steady wind speed.



RESULTS AND PERFORMANCE ANALYSIS

SNO	WIND SPEED(m/s)	AVAILABLE POWER(watts)
1	3	39.22
2	4	92.97
3	5	181.58
4	6	313.77
5	7	498.26
6	8	743.77
7	9	1059

- Power Generation: Maximum efficiency 55.07% reached 181.58 W at 5 m/s wind speed.

- Cut-in Speed: The windmill started generating power at 2 m/s, making it suitable for low-wind areas

Cost Analysis

- Total cost of materials: significantly lower than commercial small wind turbines
- Major savings due to use of recycled materials and repurposed electronic components.

Chapter 7

DISCUSSION & CONCLUSION

1) *Strengths of the Design*

- **Low Cost**: The use of recycled materials makes it affordable for rural and off-grid applications.

- **Ease of Assembly**: Simple tools and techniques were used, making it **replicable by local communities**.

- **Efficient in Low Wind Conditions**: The windmill functioned at wind speeds as low as **2 m/s**.

2) *Limitations & Challenges*

- **Lower Power Output**: Compared to commercial wind turbines, the power output is limited. **Durability Concerns**: PVC blades may degrade over time due to UV exposure. **Manual Adjustments Needed**: The windmill lacks an **automatic yaw system** to align with wind direction.

H. *Conclusion :-*

The development of a **low-cost horizontal windmill using recycled materials** proves to be a **feasible and sustainable alternative** for small-scale energy production. While the current design shows promising results, further **enhancements in material durability and power generation efficiency** can make it a viable option for off-grid rural communities.

REFERENCES

- **"Exploring the Performance of Horizontal Axis Wind Turbine in Yawed Conditions"** *Published in*: Renewable Energy, March 2025. *Summary*: This study presents experimental investigations of a scaled HAWT model tested in an atmospheric boundary layer wind tunnel, focusing on the effects of yawed inflow conditions on turbine performance.
- **"Numerical Study on Aerodynamics of Small Scale Horizontal Axis Wind Turbines"** *Published in*: Scientific Reports, December 2024. *Summary*: This paper presents a computational fluid dynamics (CFD) analysis and blade element momentum (BEM) analysis of small-scale HAWTs under various parameters, evaluating different airfoils for optimal aerodynamic performance.
- **"Bio-mimicry in the Aerodynamics of Small Horizontal Axis Wind Turbines"** *Published in*: Journal of Wind Engineering, February 2025.
Summary: This review examines the latest advancements in bio-inspired aerodynamic techniques and their potential in overcoming challenges faced by small HAWTs.
- **"Enhancing the Efficiency of Horizontal Axis Wind Turbines Through Optimization of Blade Parameters"**
Published in: Journal of Engineering, November 2024. *Summary*: This research delves into the potential of HAWTs to meet electricity needs in developing countries by optimizing blade parameters and evaluating specific airfoils for improved aerodynamic efficiency.
- **"Control Methods for Horizontal Axis Wind Turbines (HAWT)"** *Published in*: Energies, September 2024. *Summary*: This paper reviews various control strategies for the main control systems of wind turbines, including pitch, torque, and yaw control, considering multi-objective control techniques.
- **"Experimental Analysis of a Horizontal-Axis Wind Turbine with Swept Blades Using PIV Data"** *Published in*: Wind Energy Science, August 2024. *Summary*: This study presents findings from a wind tunnel experiment investigating a model wind turbine equipped with aft-swept blades, utilizing particle image

velocimetry to measure velocity fields and derive aerodynamic parameters.

- **"Current Trends and Innovations in Enhancing the Aerodynamic Performance of Small-Scale Horizontal Axis Wind Turbines"** *Published in*: ASME Open Engineering, January 2024. *Summary*: This review paper attempts to prioritize and layout strategies toward evaluating and enhancing the aerodynamic performance of small-scale HAWTs.
- **"A New Approach for Designing Small Horizontal Axis Wind Turbine Blades"** *Published in*: AIP Conference Proceedings, June 2024. *Summary*: This study focuses on optimizing the blade design of a small 5 kW wind turbine to obtain an optimal shape, aiming to increase power output and facilitate the fabrication process.
- **"The Aerodynamic Performance of Horizontal Axis Wind Turbines Under Rotation Condition"** *Published in*: Sustainability, August 2023. *Summary*: This paper analyzes the unsteady aerodynamic interaction characteristics of HAWTs near the ground, considering blade rotation effects and examining various performance parameters.
- **"Wind Turbine Enhancement via Active Flow Control Implementation"** *Published in*: arXiv preprint, July 2024. *Summary*: This research aims to enhance the efficiency of a DTU-10MW HAWT via Active Flow Control implementation and using Synthetic Jets, demonstrating a considerable power increase by managing to reattach the former separated boundary layer.