Imperial College of Science, Technology and Medicine

Imperial College Energy Society

Novel Wind Turbine Design Challenge Group II

VAWT Project Overview

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Summary

This project as part of the Energy Society involves the design, development, and analysis of a vertical axis wind turbine designed by a group of eight students from Imperial College London. The turbine is designed to generate W in unsteady, multi-directional urban wind conditions. The objective is to explore a hybrid configuration that combines a lift-based system (Straight-Bladed Darrieus) with a drag-based system (Savonius) to enhance self-starting characteristics while maintaining strong steady-state performance.

This project is structured into three sub-teams: Aerodynamics, Structures, and CAD. The Aerodynamics sub-team is responsible for selecting an optimal airfoil, conducting theoretical fluid mechanics calculations, and using CFD to validate performance. The Structures sub-team focuses on the structural analysis of beam components and performs FEA on the entire turbine structure. The CAD sub-team creates the CAD model for each design iteration, develops simplified geometry models for CFD and FEA analysis, and prepares disassembled models for manufacturing.

The final prototype will be manufactured at the Imperial College Mechanical Engineering Student Workshop, using a hybrid fabrication method that includes additive manufacturing and laser cutting.

Contents

1 Introduction

1.1 Context and Motivation

Small wind turbines have gained increasing attention as a renewable energy solution for urban and off-grid applications. As the demand for sustainable energy sources grows, the need for efficient, cost-effective, and scalable wind turbine designs becomes more critical. While Horizontal-Axis Wind Turbines (HAWTs) have dominated the industry, their reliance on specific wind directions and the requirement for larger, more complex components make them less suitable for urban environments, where wind conditions are often unpredictable and multi-directional.

In contrast, Vertical-Axis Wind Turbines (VAWTs) have several advantages, particularly in urban settings. Unlike HAWTs, VAWTs can capture wind from any direction without the need for yaw mechanisms. They also tend to have a more compact design, which is ideal for integration into buildings or other constrained spaces. However, current VAWT designs, such as the Straight-Bladed Darrieus turbine, face challenges related to low self-starting capability and suboptimal performance in low wind speeds. Additionally, the drag-based Savonius turbine, while effective at self-starting, suffers from low efficiency in steady-state operation.

1.2 Objectives

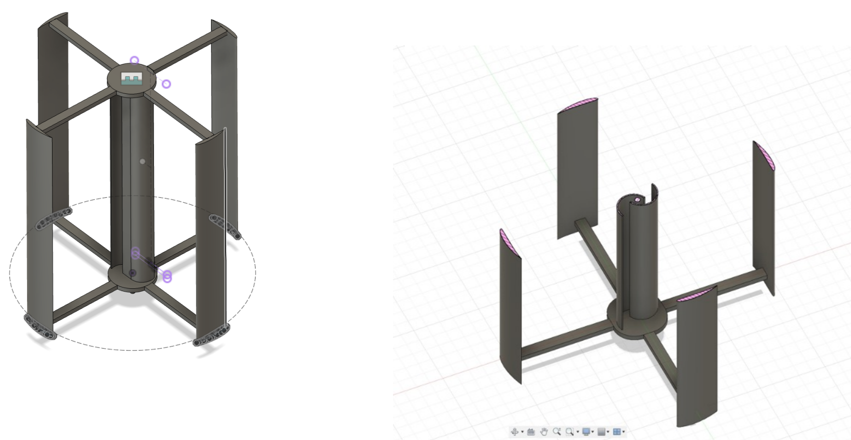
This project aims to address these limitations by exploring a hybrid VAWT design that combines the lift-based characteristics of the Straight-Bladed Darrieus turbine with the drag-based advantages of the Savonius turbine, making it better suited for urban environments with fluctuating wind conditions. The hybrid design is intended to:

1. Improve the self-starting characteristics of the system
2. Maintaining good steady-state performance

2 Design Specification

2.1 Initial Concept and Design Criteria

The fifth and most recent design iteration features a hybrid system combining the straight-bladed Darrieus turbine and the Savonius turbine. The aerodynamic body of the turbine has dimensions of $0.5\,\mathrm{m}\times0.5\,\mathrm{m}\times0.5\,\mathrm{m}$. The Savonius system is located at the centre of the turbine and has dimensions of $0.1\,\mathrm{m}\times0.1\,\mathrm{m}\times0.5\,\mathrm{m}$. The Darrieus system consists of four blades, each attached to the Savonius system via two beams. Every blade has a span of 0.5 m,a chord length of 0.082 m and is located 0.25 m from the central axis of the turbine. A picture of the CAD model can be seen in Figure 1.



(a) CAD Model (b) Cross-Sectional View

Figure 1: CAD Model and Section View

2.2 Airfoil Selection and Polar

2.2.1 SG6043

The airfoil use in the Darrieus system is the SG6043 airfoil. This is because it has a very high maximum lift to drag ratio of 39.7 at $\alpha = 8.75°$, which is very beneficial to the lift-type system. SG6043 airfoil also has a good angle of attack tolerance and a good stall behaviour. These properties ensures the optimised performance at low Reynold's number. A plot of the airfoil section is shown in Figure 2.

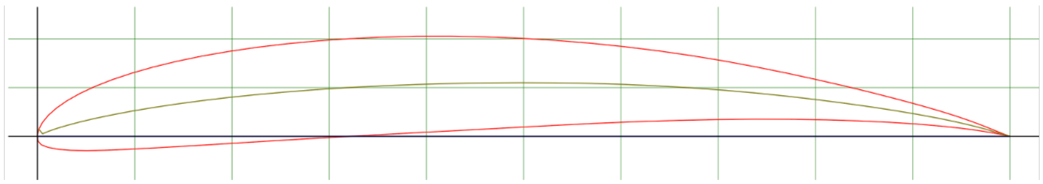


Figure 2: Airfoil Section

The airfoil polar at $Re = 5 \times 10^4$ is shown in Figure 3, it is evident that when there is a broad peak around $\alpha = 8.75°$, indicating strong adaptability in fluctuating wind conditions.

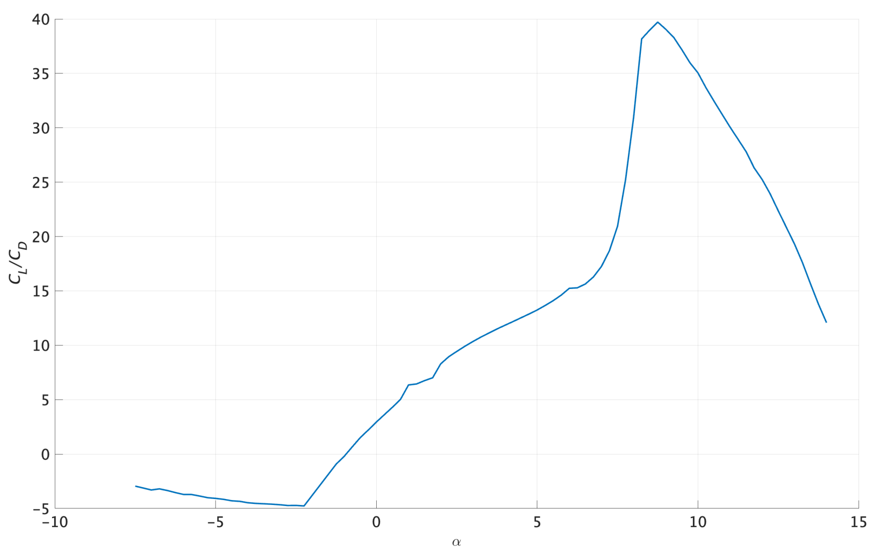


Figure 3: Airfoil Polar

2.2.2 Modelling Stall and Integration

The method used to model post-stall region is Viterna-Corrigan post stall extension method, this implies a few assumptions:

- Sinusoidal lift decay by potential flow theory
- Form drag dominance
- Static stall
- Symmetric behaviour

With these assumptions made, the airfoil polar can be extended into the post-stall region and a plot is shown by Figure 4.

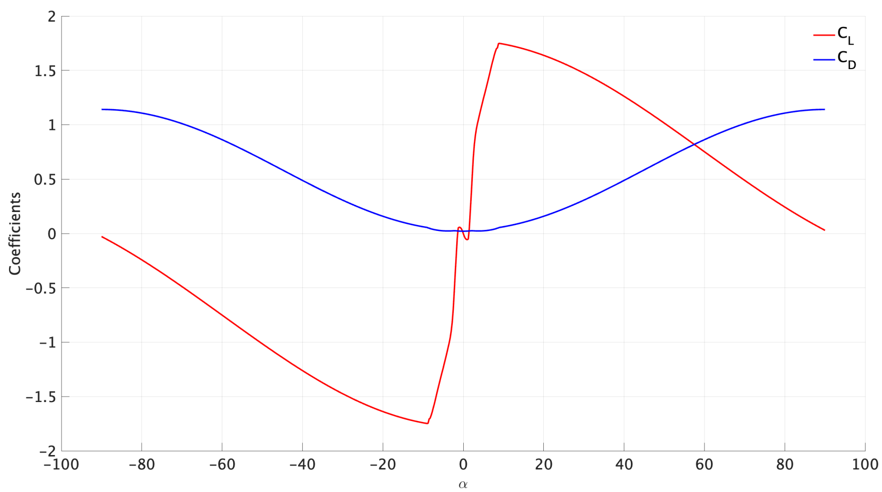


Figure 4: Extended Airfoil Polar

2.3 Savonius System Specification

The Savonius system featured the classical two blade design arranged in miss-aligned S shape. This ensures a simple design that minimises the complexity and cost. There are two plates added on top and bottom of the Savonius system for constraints and connection to beams. A cross-sectional view of the Savonius system is shown in Figure 5.

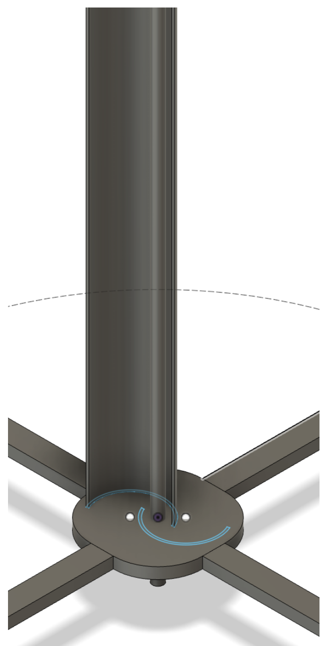


Figure 5: Savonius System Cross Section

The calculation for combined Darrieus-Savonius system is performed using CFD and will be discussed in the following sections. The empirical data for Savonius system suggests a C_M of 0.1 typically.

2.4 Manufacturing Specification

2.4.1 Materials

The turbine will primarily be constructed using two materials: PLA and plywood. Complex geometries, such as airfoil, will be manufactured using 3D printing. For simpler geometries, such as the beams connecting the blade to the Savonius system, wooden beams will be used directly. The Savonius system will combined with both plates will be made via 3D printing.

2.4.2 Surface treatment

To reduce the roughness on the surface of both systems, the 3D printed parts will be polished by sanding paper, and then covered with heat shrink film.

2.4.3 Disassembly & parts

As previously described, the model will be made in different parts and later assembled, an exploded view can be seen in Figure 6.

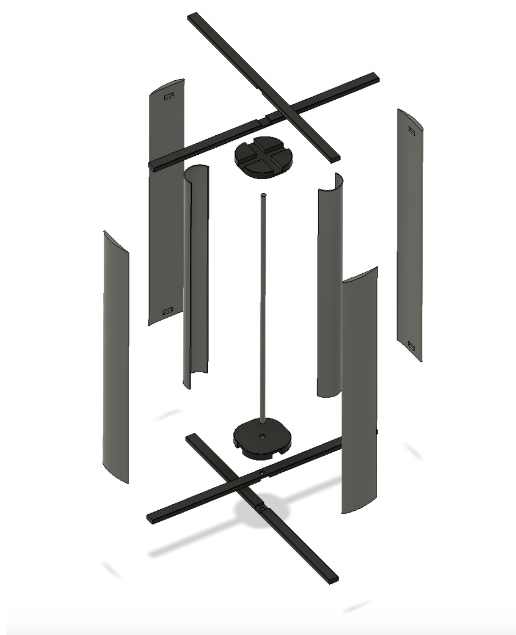


Figure 6: Exploded disassembly view

3 Calculations and Simulations

3.1 Aerodynamics

3.1.1 Theoretical Aerodynamic Moment

The airflow around the Darrieus system can be decomposed into two components: free-stream, and flow due the rotation of the turbine. Figure 7 shows this decomposition [1].

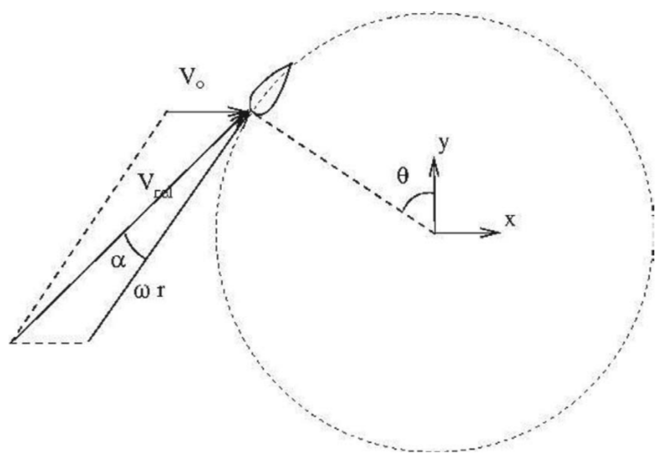


Figure 7: Flow decomposition

From the theoretical base provided by Hansen et al, the sectional moment contribution from a single blade can be calculated using the following expression:

$$l = \frac{1}{2}\rho V_{\mathrm{rel}}^2 c C_l(\alpha, Re) \tag{1}$$

$$d = \frac{1}{2}\rho V_{\mathrm{rel}}^2 c C_d(\alpha, Re) \tag{2}$$

$$p_t = l \sin\phi - d \cos\phi \tag{3}$$

Where the C_L and C_D coefficient are interpolated from the airfoil polar. Because the wind turbine is a straight blade Darrieus turbine, the drag and lift profiles of each section against azimuthal angle can be assumed to be constant throughout the span of the airfoil. Therefore, by combining the other three blades to the system with phase difference of 90°, 180°, and 270° respectively, the full sectional moment generated can be obtained. Figure 6 shows the theoretical calculation for the turbine output power calculation at 1.5 m/s uniform wind and rotating at 2 revolutions per second. The assumptions made in this calculation involves the following:

- The Reynolds number is assumed to be constant and at $Re = 5 \times 10^4$
- The turbine rotational frequency is assumed to be constant.
- No induced drag
- No flow field interruption between different blades
- The airfoil polar in stalled region is modelled using the Viterna method[2]

Figure 8 shows the theoretical result under this condition , which is likely to be the steady state operating condition in urban wind conditions.

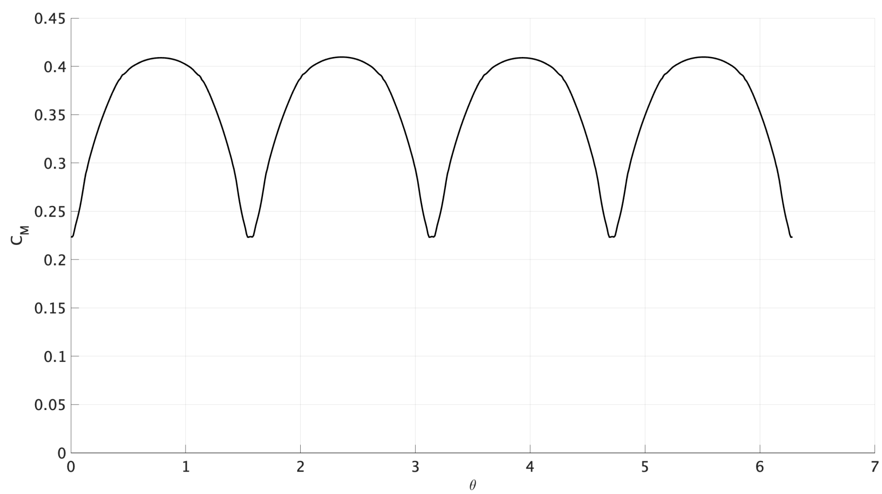


Figure 8: Theoretical Results for steady state operating condition

From Figure 6, it can be seen that the C_M varies between around 0.25 to 0.41, this translates to an average moment of 0.0193 Nm. This corresponds to a power output of 0.22 W. However, this needs to be checked against experimental results. Operations at other wind speeds will be discussed in the next sections.

3.1.2 CFD Analysis

A CFD analysis is set up with verified mesh-convergence. The conditions used for the setting are incompressible, steady, viscous and turbulent boundary layers with no-slip condition on the surface. The wall setting is the standard wind tunnel setup, featuring a velocity inlet, a pressure outlet and four slip-walls. A schematic representation for velocity profile is shown in Figure 9.

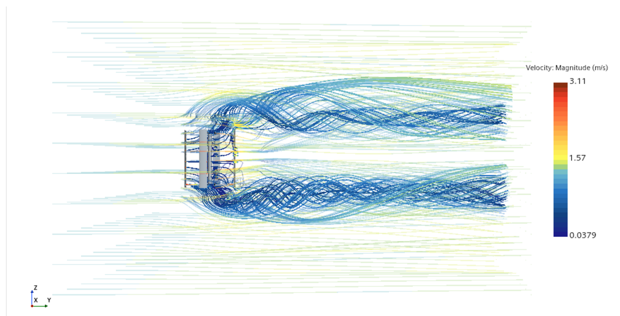


Figure 9: Schematic Velocity profile calculation

The results of the CFD analysis is shown in Figure 10, only two orientations in the quarter revolution is tested.

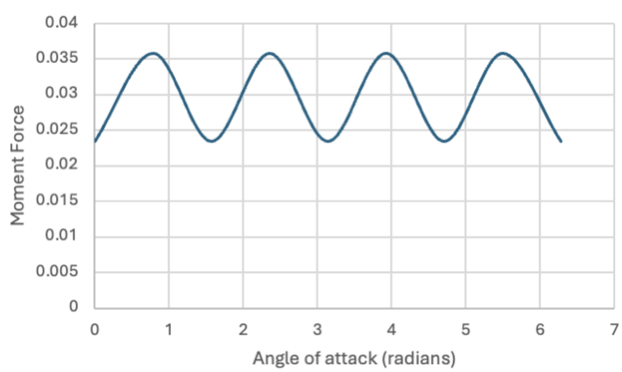


Figure 10: CFD Results

The CFD produces a result that is slightly higher (Roughly 0.006 Nm) than the theoretical calculation. This is because the CFD analysis accounts for the entire Darrieus-Savonius system.

3.2 Structural Analysis

3.2.1 Theoretical Beam Calculations

By inspection of the whole model, it can easily be seen that the airfoil and beams is where failure is most likely to happen. In this section, the loading behaviour for beams will be explored. The dynamic responses of the beam members can be modelled using Euler-Bernoulli theory, which is shown in equation 4.

$$\rho A \frac{\partial^2 v}{\partial t^2} + EI \frac{\partial^4 v}{\partial z^4} = w \tag{4}$$

The beam members in the turbine can be modelled to beam cantilever beams, with the fix end at the joint with Savonius system, and free end at the connection with the blade. Apart from the boundary conditions, the following assumption are applied to the beam members:

- The beam member is uniform and prismatic
- The beam member vibrates at its first mode

The following expression can be found by solving the differential equation:

$$\omega = \frac{1.8751^2}{l^2}\sqrt{\frac{EI}{\rho A}} \tag{5}$$

In the CAD model, length of the beam is 0.2 m and the cross-sectional area is 2×10^{-4} m^2. The material used for the beam section is ply wood with $\rho = 600\,\mathrm{kgm}^{-3}$ and $E = 10\,\mathrm{GPa}$. From these parameters, the natural frequency of vibration is calculated to be 2072 Hz; which means that dynamic structural failure will not likely to happen because there is a significant difference between the rotational angular frequency (The loading frequency) and the natural frequency of vibration.

To further analyse the structural behaviour a FEA analysis is setup to analysis the response for airfoil and will be discussed in the following sections

3.2.2 FEA analysis

A FEA analysis with verified mesh convergence is set up on the assembled model. A distributed Load of 10 N is applied outward for each blade to account for both the aerodynamic for and the centrifugal stress caused by rotation. The schematic stress distribution in the model is shown by Figure 11.

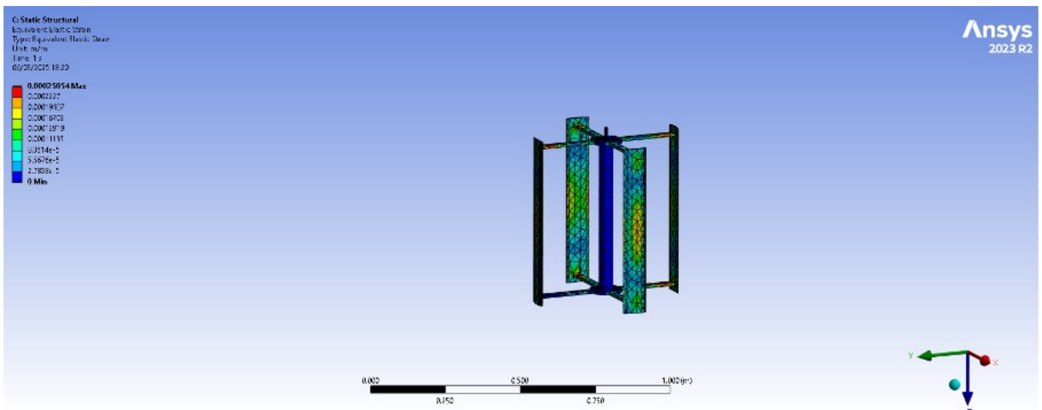


Figure 11: Stress distribution (schematic)

A representation of deformation distribution is shown in Figure 12.

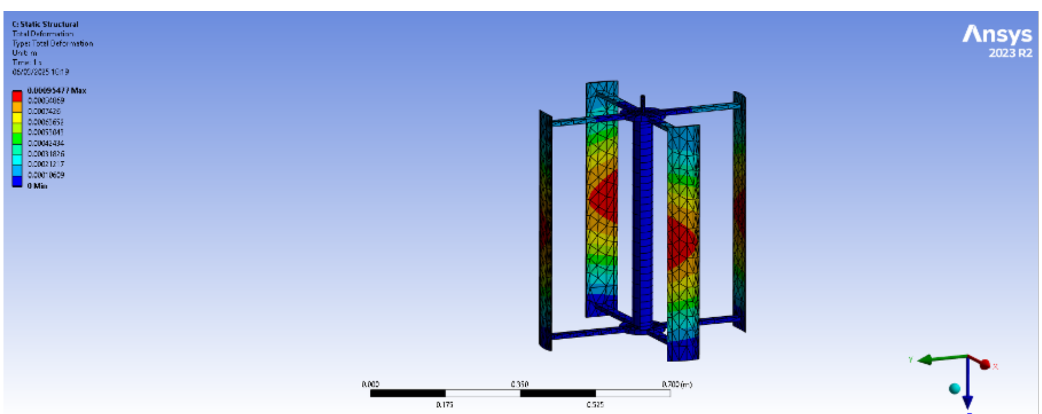


Figure 12: Deformation Distribution

It is evident that the greatest deformation occurs at mid-span, with a magnitude of 0.5 mm.

4 Analysis and Conclusion

4.1 Aerodynamics

At the Proposed cut-in wind speed, the combined system is able to produce 0.03 Nm of torque, this is very high compared to other small-sized VAWTs. This indicates that adding a drag based system on Darrieus wind turbine is very effective in improving self-starting characteristics.

Apart from the good self-starting characteristic, the good steady state output condition is maintained. From theoretical calculations, the turbine is able to produce 13.6 W of power at a wind speed of 5 m/s; and the turbine will be able to produce 34 W at a wind speed of 10 m/s theoretically.

4.2 Structures

From Euler-theory, the beam elements are unlikely to undergo dynamic failure and from FEA analysis, the airfoil components will deform within tensile strength.

4.3 Sources of Errors

There are multiple sources of errors in this analysis. They span over stall modelling and CAD idealisation:

- The Reynolds number is assumed to be constant and at $Re = 5 \times 10^4$, but it's actually varying
- No induced drag
- No flow field interruption between different blades
- The airfoil polar in stalled region is modelled using the Viterna method
- Symmetric behaviour assumption for an asymmetric airfoil.
- No Savonius theoretical calculation
- Viterna method for stalling behaviour is relatively inaccurate
- Didn't consider about joints in the model when doing structural analysis

4.4 Conclusion

Based on the good self-starting characteristics and great adaptability of the this system, this Darrieus-Savonius hybrid system is suitable for applications over a large range of scenarios:

- Low wind speed ($TSR < 2$): monitor sensors on structures
- Medium wind speed (TSR between 2 to 5): small scale emergency backup power supply
- Large wind speed ($TSR > 5$): Household applications to reduce electricity bill and potentially commercialise.

4.5 Future Work

In the next two month, the project group will manufacture a prototype and test it in the wind tunnel to collect experimental data. This will provide further validation to the calculations and simulations made.