MARMARA UNIVERSITY

FACULTY OF ENGINEERING

DESIGN ,MODELING AND ECONOMIC PERFORMANCE ANALYSIS OF A VERTICAL AXIS OF WIND TURBINE

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GRADUATION PROJECT REPORT

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by

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TABLE OF CONTENTS

ABSTRACT

The insatiable demand for electricity and the growing concerns over climate change have necessitated a shift from conventional fossil fuels to renewable energy sources. Among the various renewable energy resources, wind energy emerges as a significant contributor due to its abundance and sustainability. The thesis focuses on the design, modeling, and economic performance analysis of a Vertical Axis Wind Turbine (VAWT). A comprehensive approach involving materials selection, aerodynamic design, and Ansys modeling is employed to design the wind turbine. Furthermore, the economic performance of the designed turbine is analyzed, taking into account the construction costs. The findings suggest that the designed VAWT not only achieves high energy output efficiency but also shows promising economic viability. The study further opens avenues for research aimed at enhancing the design and performance of VAWTs.

ABBREVIATIONS

VAWT: Vertical Axis Wind Turbine

HAWT: Horizontal Axis Wind Turbine

LIST OF FIGURES

LIST OF TABLES

PAGE

1. INTRODUCTION

Wind energy is a type of renewable energy that harnesses the natural power of the wind to generate electricity (Jacobson, 2018). It is an abundant and inexhaustible source of energy that does not produce greenhouse gasses or other harmful pollutants (Mills, 2017). As of the past decade, wind energy has emerged as one of the fastest-growing sources of electricity in many countries around the world (IRENA, 2020).

The conversion of wind energy into electrical power is accomplished by wind turbines, which work on the basic principle of converting kinetic energy into mechanical energy (Sathyajith, 2006). The continuous evolution of wind turbine technology has resulted in more efficient and cost-effective ways of generating electricity, thereby increasing the potential of wind energy as a significant contributor to the global energy mix (Wiser & Bolinger, 2018).

Despite the many advantages of wind energy, challenges such as the intermittency of wind speeds, the environmental impacts of wind farm development, and the need for storage and grid integration still need to be addressed to further promote the widespread adoption of wind energy (Gross et al., 2013).

There is a need for turbines that can produce energy that can meet the energy needs for daily simple devices (such as traffic lights) in urban areas. Vertical wind turbines have been created to meet the energy needs of these simple devices.

The aim of this project is to design vertical wind turbines that can be used in urban areas.

1.1. General Information

In today's world, energy is one of the most important requirements for all countries. In the last century, with the development of technology and industry, the need for energy has increased tremendously. Petroleum and its derivatives still maintain their place as the primary energy source in energy production and consumption. However, according to many studies, the reserves of fossil fuels such as oil, natural gas and coal reserves are decreasing day by day and it is predicted that they will not be able to satisfy the increasing energy needs in the coming years. Renewable energy sources are a good alternative to satisfy energy needs. In addition, these energy sources prevent the global problems caused by the toxic and harmful gas emissions of fossil fuels.In this project, wind energy, one of the renewable energy sources, will be discussed.

1.1.1. Wind energy

Wind is used to produce electricity by converting the kinetic energy of air in motion into electricity. In modern wind turbines, wind rotates the rotor blades, which convert kinetic energy into rotational energy. This rotational energy is transferred by a shaft to the generator, thereby producing electrical energy. (irena.org, 2023)

1.1.2. Wind turbines

Wind turbines are used to produce energy from wind energy. Wind turbines convert the kinetic energy of moving air into mechanical energy and then into electrical energy. For a wind turbine to produce energy, the wind speed must be between the minimum and maximum operating speed of that wind turbine.

There are two types of wind turbines: the horizontal-axis wind turbines (HAWTs) and vertical-axis wind turbines (VAWTs). HAWTs usually have two or three long, thin blades that look like an airplane propeller. The blades are positioned so that they face directly into the wind. VAWTs have shorter, wider curved blades that resemble the beaters used in an electric mixer.

In this project, a VAWT will be designed according to a certain wind rate range in a determined area, as a wind turbine that can be used in the city and buildings will be designed.

1.2. Demand Analysis

According to the World Energy Outlook 2009 (OECD/IEA 2009), almost 100 percent of people in OECD and transition economies have access to electricity, while only 72 percent of people in developing countries have access (Table 1).(Legros, Havet, Bruce, and Bonjour, 2009)

Table 1 Demand Analysis

	Total population (in millions)	Electrification rates (%)	Total population without electricity (in millions)
World	6,692	78.2	1,456
OECD and transition economies	1,507	99.8	3
Developing countries	5,185	72	1,453

Source: World Energy Outlook 2009 (OECD/IEA 2009). Notes: The IEA estimates are based on a different system of regional classification than the UNDP classification system used for this report.

Access to energy closely correlates with poverty: insufficient access to electricity or other energy sources also means that health services, access to clean water and sanitation, and education all suffer.(Cheikhrouhou, 2011).

1.3. Importance of Wind Turbines in Renewable Energy Generation

Wind turbines play a critical role in renewable energy generation, contributing significantly to reducing carbon emissions and reliance on fossil fuels (Aitken, 2010). As wind is a renewable and sustainable source of energy, wind turbines offer an environmentally friendly solution to meet our energy needs (Lund, 2007).

Current research and development efforts in the field of wind energy focus on enhancing the efficiency, reducing the costs, and minimizing the environmental impacts of wind turbines (Smart & Stojkovic, 2011). As such, they play a crucial role in the transition towards a sustainable energy future (Kaldellis & Zafirakis, 2011).

The increasing competitiveness of wind energy, especially with respect to traditional fossil fuel-based sources of energy, has resulted in the exponential growth of wind energy installations worldwide (Wiser & Bolinger, 2018). However, the full potential of wind energy can only be realized through continuous innovation and improvement in wind turbine design and technology (Moriarty & Honnery, 2012).

1.4. The Need for Efficient Wind Turbine Design

The efficiency of a wind turbine is primarily determined by its design, which includes the shape and configuration of the blades, the size and type of the turbine, and the materials used in its construction (Manwell et al., 2009). An efficient wind turbine design is essential not only for maximizing energy output but also for ensuring the economic viability and environmental sustainability of the wind energy project (Burton et al., 2011).

Despite advances in wind turbine technology, there are still significant opportunities for improving the efficiency and reducing the cost of wind turbines through innovative design solutions (Smart & Stojkovic, 2011). This requires a comprehensive understanding of wind turbine aerodynamics, materials, and manufacturing processes, as well as the use of advanced computational modeling techniques (Chen et al., 2015).

Furthermore, efficient wind turbine design can help address some of the major challenges facing the wind energy sector, such as noise pollution, visual impact, and harm to wildlife, thereby promoting the social acceptance and sustainable development of wind energy projects (Kaldellis & Zafirakis, 2011).

1.5. Objectives and Outline of the Study

The primary objective of this study is to design, model, and analyze the economic performance of a Vertical Axis Wind Turbine (VAWT). The study aims to enhance the efficiency and economic viability of VAWTs through innovative design and modeling approaches (Li et al., 2017). It also seeks to contribute to the ongoing efforts towards achieving a sustainable energy future through the widespread adoption of wind energy (Wiser & Bolinger, 2018).

This study is organized as follows: Chapter 2 presents the materials and methods used in designing and modeling the VAWT and analyzing its economic performance. Chapter 3 presents the results and discussion of the performance analysis. Finally, Chapter 4 concludes the study and provides recommendations for future research.

2. MATERIAL AND METHOD

2.1. Introduction to Vertical Axis Wind Turbine (VAWT)

Vertical Axis Wind Turbines (VAWTs) are a type of wind turbine where the main rotor shaft is set transverse to the wind (but not necessarily vertically) while the main components are located at the base of the turbine. This arrangement allows the generator and gearbox to be located close to the ground, facilitating service and repair. VAWTs do not need to be pointed into the wind, which eliminates the need for wind-sensing and orientation mechanisms.

VAWTs come in two main types: the Darrieus and the Savonius. The Darrieus models, named after their French inventor, have a curved design that can provide high efficiency but requires strong materials to withstand the forces on the structure. On the other hand, the Savonius models are drag-type devices that consist of two or three scoops. Due to their design, they are always self-starting but have a lower efficiency.

2.2. Design of the Vertical Axis Wind Turbine

The design of a Vertical Axis Wind Turbine is a complex process that involves the careful consideration of a range of factors. These factors include the turbine's intended location, the prevailing wind conditions in that location, the intended use of the turbine, and the budget available for the project.

2.2.1. Materials selection for wind turbine

Selecting the right materials for the construction of a wind turbine is crucial as it directly affects its performance, lifespan, and maintenance requirements. Typically, the materials used to build a wind turbine include steel, aluminium, copper, and various types of plastic and composite materials.

The blades of the turbine, one of the most important components, are often made from lightweight yet sturdy materials such as composites of glass or carbon fiber. The tower is usually made of steel or aluminium. The generator, which converts the mechanical energy from the wind into electrical energy, typically includes copper and a range of other materials.

2.2.2. Aerodynamic design of VAWT

The aerodynamic design of a VAWT is significantly different from that of a Horizontal Axis Wind Turbine (HAWT). The blades of a VAWT are designed in such a way that they harness the kinetic energy of the wind in the most efficient manner.

The shape and configuration of the blades have a significant impact on the turbine's performance. The blade shape must be carefully designed to minimize drag and maximize lift. This can be achieved by employing airfoil shapes, similar to those used in airplane wings.

Furthermore, the number and arrangement of the blades also affect the turbine's performance. While a larger number of blades increase the start-up torque, it may also increase the drag. Therefore, a balance needs to be struck between the number of blades and the overall aerodynamic efficiency of the turbine.

The orientation of the blades also plays a significant role. In VAWTs, the blades rotate around the vertical axis, which means they can capture wind from all directions. This is particularly beneficial in areas where the wind direction is highly variable.

In conclusion, the design of a VAWT is a complex process that requires a careful balance of various factors. It is essential to select the right materials and optimize the aerodynamic design to ensure the highest possible efficiency of the turbine.

2.3. Methodology for Performance Analysis

The performance of a VAWT is evaluated in terms of its power output, which is a function of the wind speed, air density, and the design of the turbine. Accurate prediction of the turbine's performance under different wind conditions is critical for its successful operation.Furthermore , The universal standard for evaluating the performance of a wind turbine is a plot of the Power Factor vs. Tip Speed Ratio performance curve. In performance measurements and comparisons of wind turbines, tip speed ratio (TSR) and power output or coefficient graphs are used.

2.4. General Operation of Turbines

The moving air hits the blades and turns the propellers. The propellers convert kinetic energy into mechanical energy in the rotor. Afterwards, the rotational movement of the rotor shaft is accelerated and transferred to the generator. Thus, electrical energy is produced by electromagnetic induction. Unlike old-style windmills, a modern wind turbine uses not only the power of the wind but also aerodynamic principles to move the blades. It is possible to talk about some aerodynamic forces that enable the rotors to work, which converts kinetic energy into mechanical energy. These are drag and lift forces. The moving air is intended to rotate the blade-like propellers. When the wind touches the blades, a pressure difference occurs and the propellers rotate.

2.5. Active VAWT

The use of aerodynamic effect (lift) –The drag type takes less energy from the wind but has a higher torque and is used for mechanical applications such as pumping water. The most representative model of drag-type VAWTs is the Savonius –Darrieus and H-rotor.

2.5.1. Darrieus

Darrieus turbine has long, thin blades in the shape of loops connected to the top and bottom of the axle; it is often called an eggbeater windmill.They have good efficiency, but produce large torque ripple and cyclic stress on the tower, which contributes to poor reliability. Also, they generally require some external power source, or an additional Savonius rotor, to start turning, because the starting torque is very low.

2.5.2. H-Rotor

It is one of the most important RTs with a vertical axis. With the version of Darrieus RT.It is a more complex type of turbine. Darrirus differed from RT by two important differences. These:The aerodynamic profile is straight,Pitch control is applied to the wings.

The tensile stress on the blades of the Darrieus wind turbine has a slight slope and therefore the tensile stresses on the blades are minimized. However, since its wings have a geometrically formed aerodynamic profile, they are high performance.

2.6. Reactive VAWT

The use of thrusting force (drag) –The lift type uses an aerodynamic airfoil to create a lift force; they can move quicker than the wind flow. This kind of windmill is used for the generation of electricity. The most representative model of a lift-type VAWT is the Darrieus turbine; its blades have a troposkien shape which is appropriate for standing high centrifugal forces –Savonius and differently called cup /bucket /drum /carousel /scoop bladed-rotors.

2.6.1. Savonius

Recently a hybrid approach to VAWT is becoming more noticeable, where active rotors are combined with reactive ones. Smaller, reactive VAWT are mounted on the larger active VAWT's shaft. Reactive VAWT is used as a starter for the active VAWT. Hybrid approach to electrical generation is also observed in developing hybrid renewable energy plants with solar and wind power. Sustainable development also requires high economic performance analysis of the renewable investments (for instance with the use of discounted methods, so comparison between HAWT and VAWT economic performance is also available.

When we examine the general vertical wind wind types with their pros and cons, and as a result of the comparison of these types of various articles among themselves, it seems that the right choice for us to be H-rotor vawt as the wind type acceptance is for now.

2.7. The Selection of the Wind Turbine Model

The wind turbine is the fundamental component of a wind park's equipment. Consequently, the selection of the appropriate wind turbine model constitutes one of the most important stages of a wind park project's development. The selection of a wind turbine model is performed on the basis of several parameters, the most important of which are mentioned below:

- the wind turbine's nominal power
- the wind turbine's physical dimensions
- the available area on the wind park installation site in relation to the wind turbine's nominal power
- the available wind potential
- several peculiarities seen in the general geographical territory of the installation site
- restrictions caused by environmental impacts and human activities
- the demand of the utility for certain specifications regarding the quality of the electricity produced from the wind turbine
- the existing technical infrastructure at the installation site (site accessibility)
- the wind turbines' purchase cost

the delivery time of the manufacturer.

2.8. Material Selection

In blades, high density polyethylene (HDPE) was chosen because of its low cost and light structure.

In structural components, steel-aluminum alloys are used to provide stability and support to the turbine.

Bearings and seals are selected in stainless steel and bronze for smooth rotation, low friction, preventing wear and corrosion.

Generators are separate from the turbine structure. Generator selection will be discussed in the next sections.

2.9. Economic Performance Analysis

The economic performance of a wind turbine is as important as its technical performance. It determines the viability of the wind energy project. The costs associated with the construction and operation of the wind turbine need to be weighed against the financial benefits from the generated electricity.

2.9.1. Cost estimation of wind turbine construction and maintenance

The cost estimation of wind turbine construction involves calculating the costs of materials, manufacturing, transportation, and installation. The cost of the materials depends on the size of the turbine and the type of materials used. The manufacturing costs include the costs of fabricating the parts and assembling the turbine. Transportation costs involve moving the parts from the manufacturing site to the installation site. Installation costs include site preparation, assembly, and connection to the electrical grid.

Once the turbine is operational, it requires regular maintenance to ensure its smooth operation. Maintenance costs include routine inspections, repair, and replacement of parts, and can be significant over the lifetime of the turbine.

In this project; maintenance and installation costs are ignored.

2.9.2. Analysis of return on investment

The return on investment (ROI) is a key indicator of the economic performance of a wind turbine. It is calculated by comparing the costs of the turbine with the income from selling the generated electricity. The ROI helps in determining the payback period, which is the time it takes for the income from the turbine to cover its costs.

The income from a wind turbine depends on the price of electricity and the amount of electricity the turbine generates. The price of electricity varies depending on the location and the policies in place. The amount of electricity generated depends on the wind conditions at the site and the performance of the turbine.

In conclusion, the economic performance analysis of a wind turbine involves estimating the costs and income, and analyzing the return on investment. This analysis is crucial for the decision-making process in wind energy projects.

3. AEORDYNAMIC ANALYSIS

In this section, rotor design parameters required for aerodynamic analysis will be explained. At the same time, we will show the models that can be used in vertical wind turbines and we will talk about which one to use. After the parameters are determined and the model is found, the flow chart of the program that we will analyze will be shown and information will be given about how the program works.

3.1. Aerodynamic

Aerodynamics is the way air moves around things. The rules of aerodynamics explain how an airplane is able to fly. Anything that moves through air reacts to aerodynamics. A rocket blasting off the launch pad and a kite in the sky react to aerodynamics. Aerodynamics even acts on cars, since air flows around cars.(nasa.gov, 2017)

3.2. Aerodynamic in a Wind Turbine

A wind turbine turns wind energy into electricity using the aerodynamic force from the rotor blades, which work like an airplane wing or helicopter rotor blade. When wind flows across the blade, the air pressure on one side of the blade decreases. The difference in air pressure across the two sides of the blade creates both lift and drag. The force of the lift is stronger than the drag and this causes the rotor to spin. The rotor connects to the generator, either directly (if it's a direct drive turbine) or through a shaft and a series of gears (a gearbox) that speed up the rotation and allow for a physically smaller generator. This translation of aerodynamic force to rotation of a generator creates electricity. (energy.gov, 2023)

3.3. Design Parameters

The wind turbine parameters considered in the design process are:

- Swept area
- Power and power coefficient
- Tip speed ratio
- Blade chord
- Number of blades
- Solidity
- Initial angle of attack

3.3.1. Swept area

The swept area is the section of air that surrounds the turbine while it is in motion. The area we find here is the area where the wind acts on the turbine. The swept area is the section of air that encloses the turbine in its movement, the shape of the swept area depends on the rotor configuration, this way the swept area of an HAWT is circular shaped while for a straight-bladed vertical axis wind turbine the swept area has a rectangular shape.(Castillo,2011)

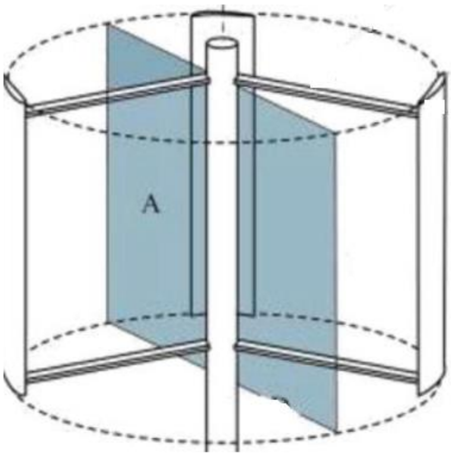


Figure 1: The swept area in the wind turbine

General formula:

$$S = 2 \times R \times L \quad (3.1)$$

where S is the swept area [m^2], R is the rotor radius [m], and L is the blade length [m]

3.3.2. Power and power coefficient

Wind power or wind energy describes the process by which the wind is used to generate mechanical power or electricity. Wind turbines convert the kinetic energy in the wind into mechanical power.(windexchange.com,2023)

The power available from wind for a vertical axis wind turbine can be found from

the following formula:

$$Pr = \frac{1}{2} \times \rho \times S \times V_0 \quad (3.2)$$

Where V_0 is the velocity of the wind [m/s] and ρ is the air density [kg/m^3], the density used its standard sea level value (1.225 kg/m^3), for other values the source

The power coefficient is defined as the ratio of the power extracted by the wind turbine to the energy available in the wind stream. The Power Factor allows us to calculate the total amount of power produced by a wind turbine from the total energy available in the wind at a given wind speed. (Jamdade, V. Patil ve B. Patil, 2013)

$$Cp = \frac{P_t}{P_r} \tag{3.3}$$

where Pt is torque power, Pr is total tower of wind.

3.3.3. Tip speed ratio

Blade Tip Speed Ratio expresses the ratio between the wind speed and the speed of the tips of the wind turbine blades. It is an important parameter to determine the aerodynamic performance and efficiency of the turbine.

$$TSR = \frac{R*\omega}{V_0} \tag{3.4}$$

where ω is the angular speed [rad/s], R the rotor radius [m] and V_o the ambient wind speed [m/s]. Each rotor design has an optimal tip speed ratio at which the maximum power extraction is achieved.

3.3.4. Blade chord

The chord is the length between leading edge and trailing edge of the blade profile. The blade thickness and shape is determined by the airfoil used, in this case it will be a NACA airfoil, where the blade curvature and maximum thickness are defined as percentage of the chord. (Castillo,2011)

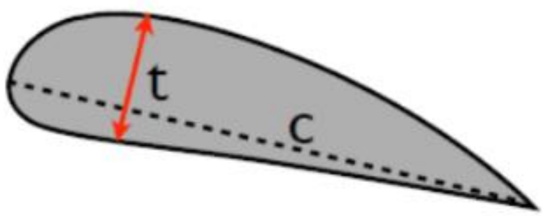


Figure 2: The blade chord in the wind turbine

3.3.5. Number of blades

The blade is the element that starts to rotate as a result of the wind blowing in wind turbines and helps the turbine to generate power.

The number of blades has a direct effect on balancing the aerodynamic loads and the operation of the turbine. The increase and decrease in the number of blades has a direct effect on the turbine effect.

3.3.6. Solidity

Solidity shows the ratio of the overall area of the blades over the swept area of the turbine and is defined as (Rezaeiha, 2018)

$$\sigma = \frac{N * c}{R} \tag{3.5}$$

where N is the number of blades, c is the blade chord, R is the rotor radius.

It is considered that each blade sweeps the area twice. So solidity can be altered either by changing the number of blades or the blade chord or rotor radius. Solidity determines when the assumptions of the momentum models are applicable, and only when using high $\sigma \geq 0.4$ a self starting turbine is achieved (Tong, 2010).

3.3.7. Initial angle of attack

The initial angle of attack is the angle the blade has regarding its trajectory, considering negative the angle that locates the blade's leading edge inside the circumference described by the blade path.

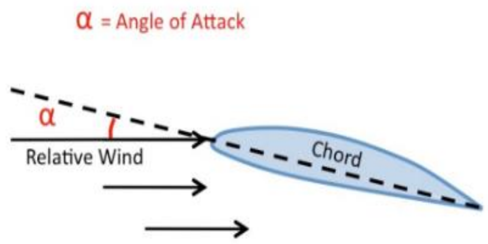


Figure 3: The blade chord in the wind turbine

3.4. Aerodynamic Model

There are some aerodynamic analysis methods used for vertically oriented wind turbines. These methods are;

- Stochastic Wind Model
- Three-Dimensional Viscous Model
- Dynamic Stall Simulation Model
- Momentum Model

We chose the Momentum model for our design . The momentum model provides a simple and fast approach.In this model, the variation of the wind flow to the turbine is calculated by simple calculations. The momentum model was used for the aerodynamic analysis of these objects.

3.4.1. Momentum model

The swept volume of the rotor is divided into adjacent, aerodynamically independent, streamtubes; each one is identified by his middle θ angle, which is defined as the angle between the direction of the free stream velocity and the position of the streamtube in the rotor (see Figure 3).

The analysis of the flow conditions is made on each streamtube using a combination of the momentum and blade element theories, the former uses the conservation of the angular and linear momentum principle and the later divides the blade in N elements and analyzes the forces on the blades (lift and drag) as a function of blade shape. It is assumed that the wind velocity experiences a deceleration near the rotor, if we represent the front and rear part of the turbine by two disks in series, the velocity will be decelerated two times, one for the upstream and the other for the downstream.

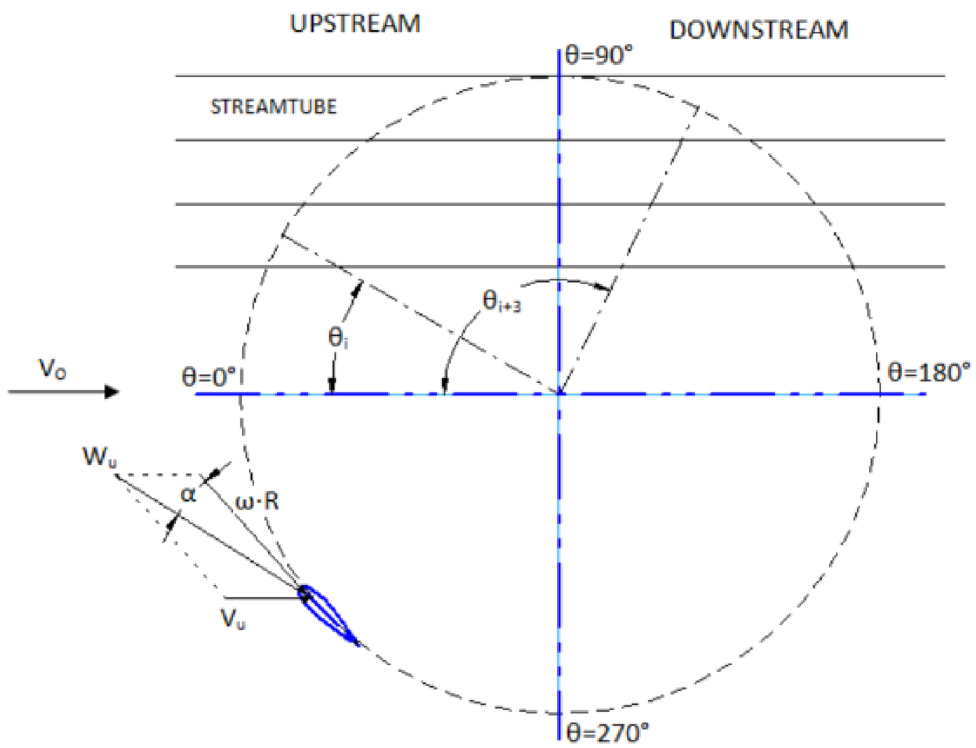


Figure 4: Momentum model

According to Paraschivoiu (2002) the induced velocities decrease in the axial streamtube direction in the following manner:

$$Vu = V_0 * au \qquad (3.6)$$

where Vu is the upstream induced velocity, Vo is the free stream air velocity and a_u is the upstream interference factor, which is less than 1 as the induced velocity is less than the ambient velocity.

In the middle plane between the upstream and downstream there is an equilibrium-induced velocity V_e:

$$Ve = V_0 * (2au - 1) \qquad (3.7)$$

Finally, for the downstream part of the rotor, the corresponding induced velocity is:

$$Vd = Ve * ad \qquad (3.8)$$

where V_d is the downstream induced velocity and ad is the downstream interference factor which is smaller than the upstream interference factor.

Knowing the induced velocities all around the blade trajectory will allow us to calculate the lift and drag forces associated to every blade position and then, these forces can be related to the torque and power coefficient produced by the wind turbine.

The resultant air velocity that the blade sees is dependent on the induced velocity and the local tip speed ratio:

$$Wu = \sqrt{[Vu^2[TSR - sin^2\theta]^2 + cos^2\theta} \qquad (3.9)$$

where W_u is the resultant air velocity and TSR is the local tip speed ratio defined as:

$$\mathrm{TSR}=\mathrm{R}*\frac{\omega}{V_u} \qquad (3.10)$$

where R is the rotor radius and ω is the angular speed.

The resultant air velocity is used then to determine the local Reynolds number of the blade.

$$Re_b = \frac{Wu * c}{K_v} \qquad (3.11)$$

Where Re_b is the local Reynolds number, c is the blade chord and K_v is the kinematic viscosity of the air, which has a reference value of $1.4607*10^{-5}$ [m^2/s] for an air temperature of 15°C (Aerospaceweb.org, 2005).

The equation for the angle of attack of the blade has been taken from Paraschivoiu (2002), the result has been demonstrated in order to ensure what is considered the 0° of the azimuth angle (θ) and also what is considered a negative angle of attack.

$$\alpha = \arcsin\left(\frac{\cos\theta \ \cos\alpha_0 - \ (X - \sin\theta) \ \sin\alpha_0}{\sqrt{[(TSR - \sin^2\theta)^2 + (\cos^2\theta)]}}\right) \qquad (3.12)$$

where α is the angle of attack which is defined as the angle between the blade chord and the resultant air velocity vector.

The previous equation allows the introduction of an initial angle of attack a_0 different from 0 °. It considers positive angles of attack those which have the relative wind speed vector outside the rotor as in Figure , which occurs in the whole upstream half of the rotor.

The local Reynolds number and the angle of attack are then used to find the corresponding lift and drag coefficients using double interpolation (i.e. one interpolation for the Reynolds number and another for the angle of attack). The data tables had been extracted from Sheldahl and Klimas (1981).

The normal and tangential coefficients can be calculated using:

$$Cn = Cl * cos\alpha + Cd * sin\alpha \qquad (3.13)$$

$Ct = Cl * sin\alpha - Cd * cos\alpha$ (3.14)

where Cn and Ct are the normal and tangential coefficients respectively and Cl and Cd are the lift and drag coefficients.

According to Paraschivoiu, using the blade element theory and the momentum equation, the upwind flow conditions can be characterized by fup:

$$fup = \frac{N\,c}{8\pi R}\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} |\sec\theta|\ (Cn\ \cos\theta - Ct\ \sin\theta)\ d\theta \tag{3.15}$$

where N is the number of blades.

Then the interference factor can be obtained by:

$$au = \frac{\pi}{fup+\pi} \tag{3.16}$$

This is repeated for each streamtube position and once the upstream induced velocities have been calculated, the downstream half is calculated using the same set of formulas, interchanging the upstream induced velocity Vu by the downstream induced velocity Vd.

The tangential and normal forces as function of the azimuth angle θ are calculated the same way as lift and drag forces in an airfoil:

$$Fn(\theta) = \frac{1}{2} * \rho * c * L * W^2 * Cn \tag{3.17}$$

$$Ft(\theta) = \frac{1}{2} * \rho * c * L * W^2 * Ct \tag{3.18}$$

where Fn and Ft are the normal and tangential force respectively, ρ is the air density [kg/m3], c is the blade chord [m], L is the blade length [m] and W is the relative wind speed.

The Torque produced by a blade is calculated using a combination between the Lift and Torque formulas.

$$Q(\theta) = \frac{1}{2} * \rho * c * R * L * Ct * W^2 \qquad (3.19)$$

The average torque produced by the upstream half of the rotor (N/2 blades) is estimated averaging the contributions of each streamtube:

$$Qav = \frac{N}{2\pi} \int_{\frac{\pi}{2}}^{\frac{\pi}{2}} \quad Q(\theta) * d\theta \qquad (3.20)$$

In order to work with non-dimensional magnitudes the average torque coefficient Cqav is calculated by:

$$Cq_{av} = \frac{Q_{av}}{\frac{1}{2} * \rho * Vo^2 * S * R} \qquad (3.21)$$

And finally the upstream half power coefficient Cpu is calculated with:

$$Cpu = Cqu_{av} * Xt \qquad (3.22)$$

where Xt is the rotor tip speed ratio which is calculated by:

$$Xt = \frac{R * \omega}{V_0} \qquad (3.23)$$

The average torque and power coefficient for the downstream half of the rotor are calculated using the same set of formulas.

The total power coefficient of the rotor is calculated then adding the two contributions:

$$Cpt = Cpd + Cpu \qquad (3.24)$$

where Cpt and Cpd are the total and downstream power coefficients respectively. (Castillo,2011)

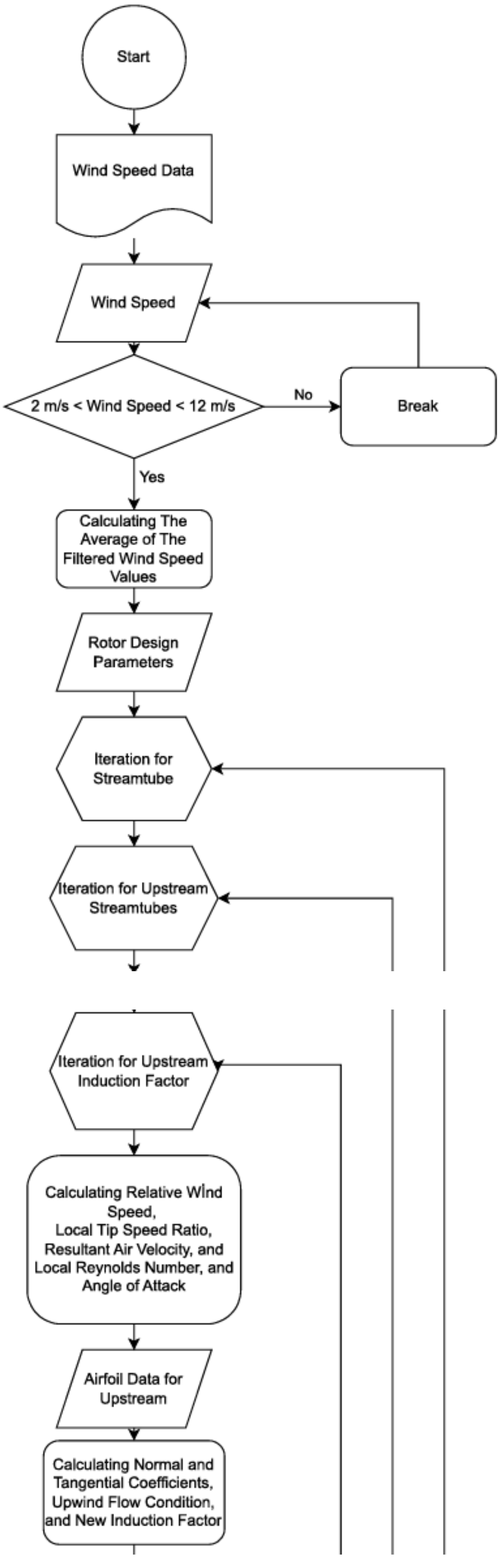
The momentum model provides a simple and fast approach. In this model, the variation of the wind flow to the turbine is calculated with simple calculations.This model is generally used in energy efficiency evaluations. Considering these items, the momentum model was used for the aerodynamic analysis.

3.5. Algorithm

Matlab code has been developed to understand the operation of the wind turbine shown in the appendix section. With this code, values such as power coefficient and torque can be calculated.

The algorithm has inputs values such as wind turbine parameters, number of streamtubes, air speed, air parameters, and airfoil lift and drag coefficients which depend on the Reynolds number and angle of attack.

The program iteratively calculates the induction factor, relative wind velocity, Reynolds number, angle of attack, normal, and tangential forces for each streamtube.


Start
Wind Speed Data
Wind Speed
2 m/s < Wind Speed < 12 m/s
No
Break
Yes
Calculating The Average of The Filtered Wind Speed Values
Rotor Design Parameters
Iteration for Streamtube
Iteration for Upstream Streamtubes
Iteration for Upstream Induction Factor
Calculating Relative Wİnd Speed, Local Tip Speed Ratio, Resultant Air Velocity, and Local Reynolds Number, and Angle of Attack
Airfoil Data for Upstream
Calculating Normal and Tangential Coefficients, Upwind Flow Condition, and New Induction Factor

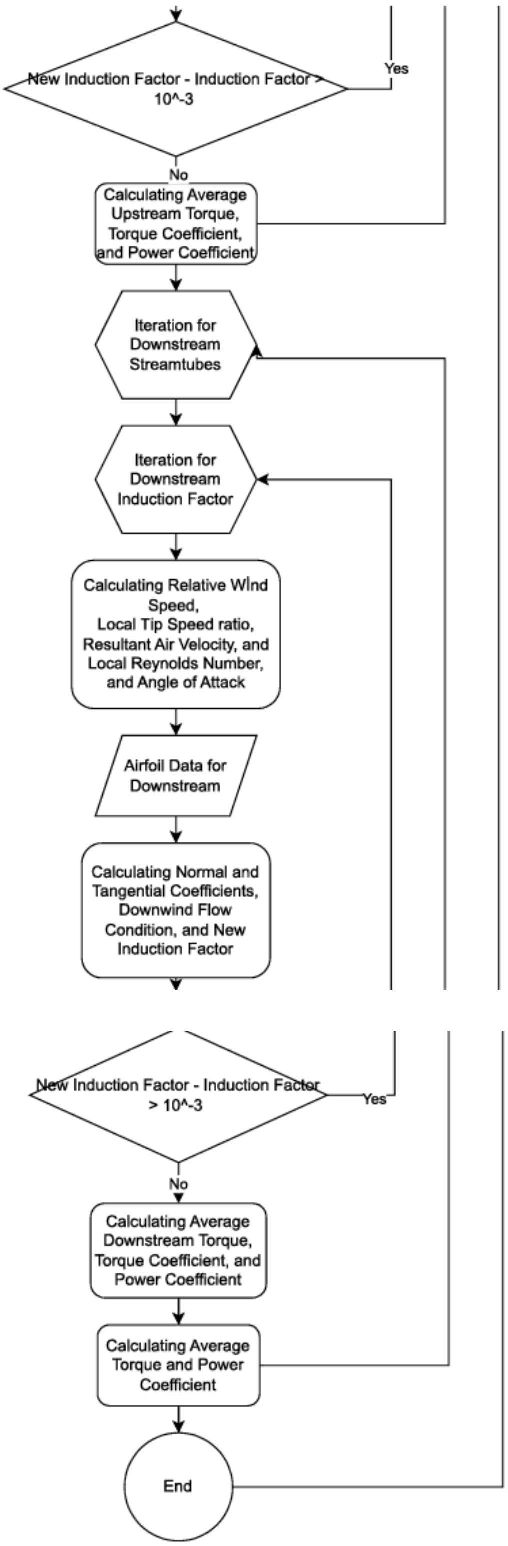


Figure 5: Flowchart of program simulation

Torque and power coefficient values are calculated by integration method at each blade position. These values provide a better understanding of the wind turbine.

3.5.1. Number of streamtubes used

10 streamtubes were used for the whole process. This means that wind conditions at blade positions are evaluated in 18º increments.

3.6. Rotor Design

In order for the wind turbine to work more efficiently with the wind speed at the location where it will be located, the design parameters have been optimized. The optimization process was carried out by looking at the power coefficient production at each value. Power efficient vs. tip speed ratio graphs were used. Each parameter was collected in a single graphic by giving different values in itself and the values with high efficiency were used for the wind turbine.

During the optimization process, some parameters need to be fixed in line with the desired targets. These; velocity, density, dynamic viscosity of the fluid, and blade length. Since it is the most ideal size that can be used in cities, this value is desired to be kept constant. The wing length was taken as 2 meters. In our wind speed value, an average value has been taken based on the hourly results of Pendik district covering a year from Metroblue.com website. This average value is 4.14 m/s. Optimization parameters are design parameters.

For the optimization process, we need to use specific and logical initial parameters. Our optimization parameters, whose fixed values will change externally, are taken from Castillo's thesis due to the similarity in size and wind speed.(Castillo,2011)

Starting Parameters;

Table 3. 2. Starting values of the turbine parameters for the optimization process

Symbol	**Parameter**	**Starting Value**
V_0	Air Speed	4.72 m/s
R	Rotor Radius	1.00 m
c	Blade Chord	0.30 m
L	Blade Length	2.00 m
N	Number of Blades	3
α_0	Initial Angle of Attack	0^{o}

Air velocity values are taken from metroblue.com website for 1 year and 24 hours for Pendik district. Since our wind turbine will operate between 2 m/s and 12 m/s, the air speed value is found by taking the average of the wind speed values in this value range.

3.7. Optimal Tip Speed Ratio

When designing turbine blades, the key issue is to assess the optimal tip speed ratio. The optimal design of tip speed ratio (TSR) will directly affect the power generated and, consequently, the effectiveness of the investment made. (sciencedirect.com, 2023)

Here, we can determine the optimal blade tip speed ratio for our wind turbine by entering the value ranges of the wind speed between 2 m/s and 12 m/s. At the same time, we can determine the range of blade tip speed ratio that our wind turbine will change. We will use our determined wing tip speed ratio in the graphics.

Optimal wing tip speed ratio is found with torque and TSR graph. We will examine the change of our torque with the speed we give at certain intervals on the graph.

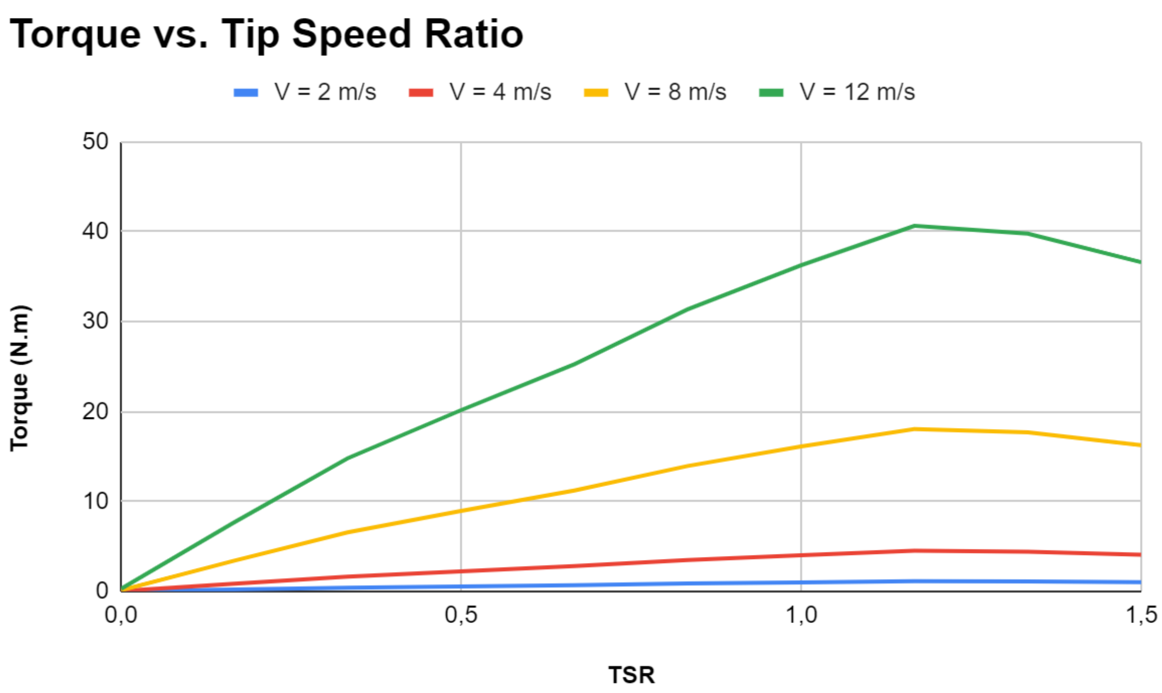


Figure 6: Torque vs. TSR at 2 m/s, 4m/s, 8m/s, and 12m/s

As we can see from the graph above, the torque values of the wind turbine at different speeds cause a decrease in the tip speed ratio of 1.1. This decrease indicates that the optimal wing tip speed ratio is out of the way. We will take our optimal tip speed ratio of 1. Tip speed ratio range is taken from 0 to 1.

3.8. Airfoil Selection

The blade profile is one of the most important parameters that must be changed for the efficiency of the wind turbine. Airfoil, the most suitable profile must be determined in order for the air flow to hold and rotate the wind turbine.

Profiles depend on the Reynolds number and angle of attack, which depends on the wind speed. Considering the initial parameters, the Reynolds number is approximately between 75000 and 150000. The angle of attack ranges from 1 degree to 80 degrees. Airfoil profiles that can comply with these values are NACA0015, NACA0012 and NACA2412 profiles. The geometry values and shapes of these profiles are given below.

These profiles have different lift and drag values because their geometry is different. It provides lift and drag coefficients for aerodynamic analysis. Lift and drag coefficient values were obtained using the XFoil program.

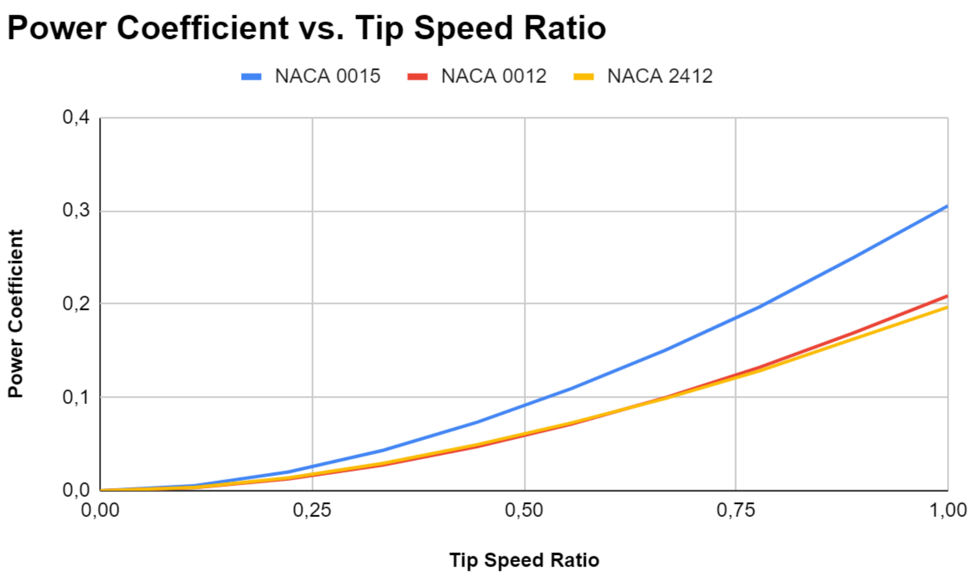


Figure 7: Power Coefficient compression between NACA0015, NACA0012, and NACA2412

Airfoil types were compared using the matlab program. The comparison was made by looking at the power coefficient. As a result of their own lift and drag coefficient inputs, airfoil types were determined by efficiency as shown in the power coefficient vs. tip speed ratio graph. As a result of the comparison, it has been seen that the NACA0015 airfoil type can work more efficiently than the others. The values of this profile will be used in future calculations.

3.9. Rotor Dimension

Blade length and rotor radius have a significant effect on the torque behavior of the turbine, as can be understood from the torque equation. In general, the larger these parameters, the greater the torque produced. These parameters are also included in the stiffness calculation. Stiffness becomes an important parameter when downscaling or upscaling wind turbines and also determines the applicability of the momentum model. Radius and blade variation analysis is done while maintaining a constant swept area.

Applying the maximum power coefficient of the rotor radius to the wind turbine will increase the effect of the wind turbines. For this, we need to obtain maximum efficiency by entering various wing radius values with our tip speed ratio versus power coefficient graph.

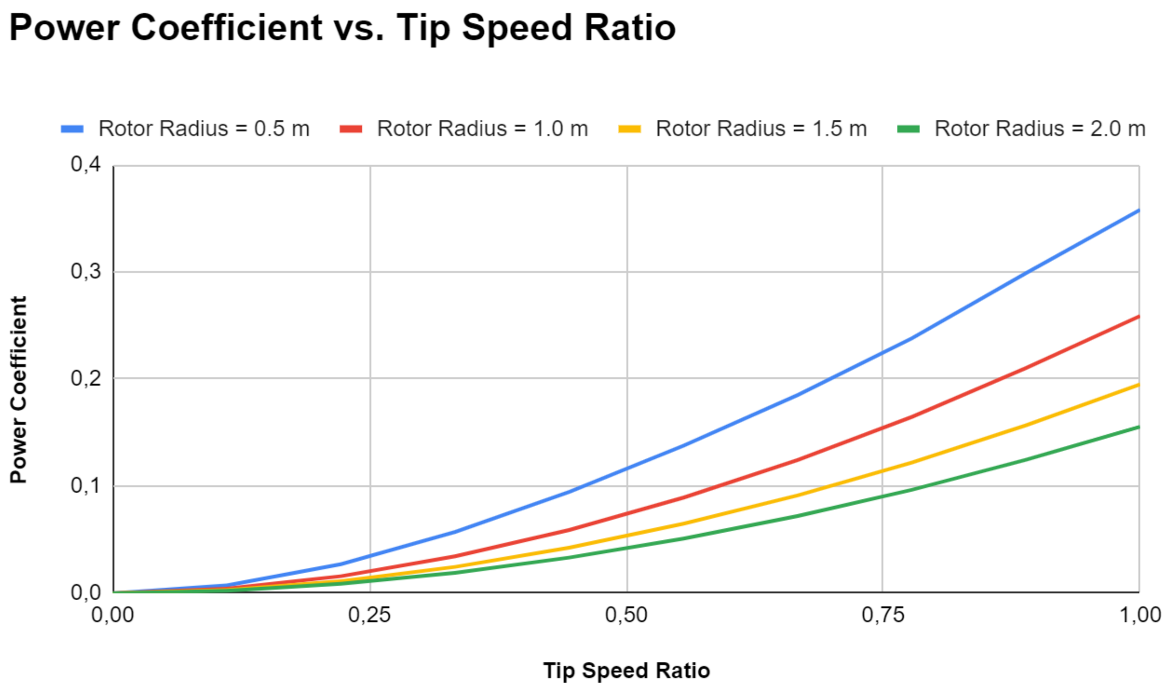


Figure 8: Rotor Radius comparison between 0.5m, 1m, 1.5m, and 2m.

The rotor radius may be within a certain range for the wind turbine at hand. By examining the values in this value range one by one, which value will be more efficient for the wind turbine is obtained from the tip speed ratio versus power coefficient graph. After the observation, it is seen that the optimum value for the rotor radius is 0.5 meters.

3.10. Solidity

The chord length of the VAWT wing affects its aerodynamic efficiency. A longer beam length can potentially provide higher lift and lower drag, resulting in increased turbine overall efficiency. However, there is an optimal beam length for a given turbine design, and increasing the beam length beyond this point can result in diminished returns or even reduced performance. (Manwell, McGowan, and Rogers, 2019)

Here, the effects of different chord lengths on the wind turbine will be examined. At the same time, the best chord length for the wind turbine will be obtained. Tip speed ratio versus power coefficient graph will be used in the examination of chord lengths.

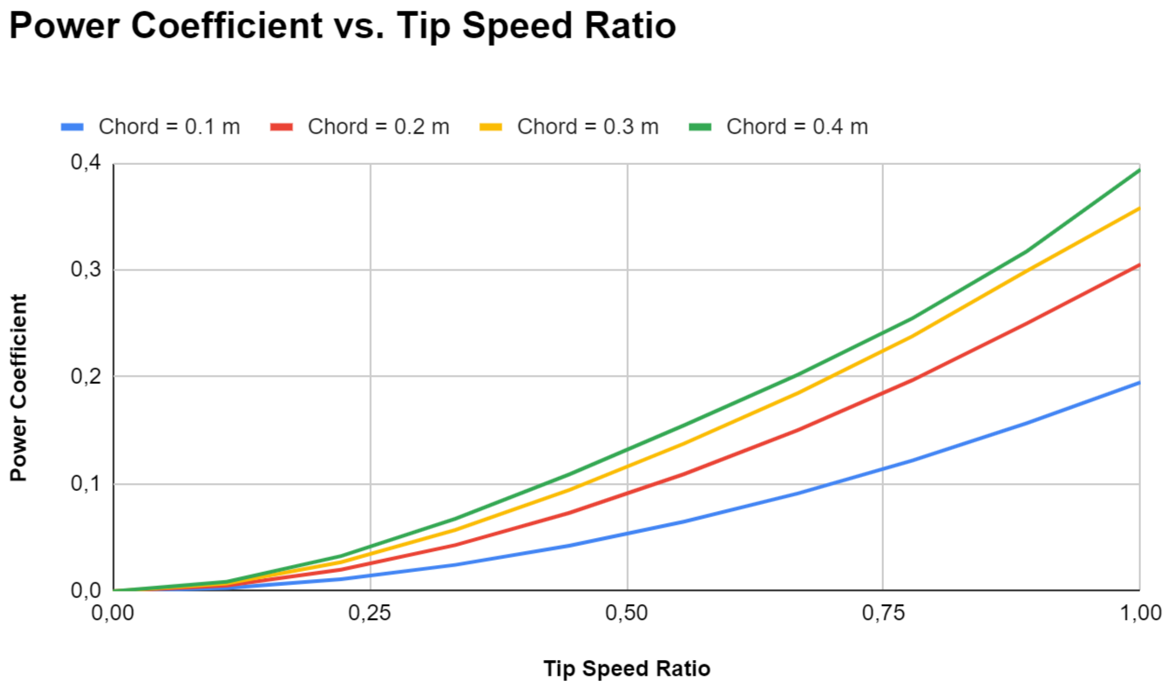


Figure 9: Chord Length comparison between 0.1m, 0.2m, 0.3m, and 0.4.

The chord length may be within a certain range for the wind turbine at hand. The values in this value range are examined one by one and the most efficient value for the wind turbine is obtained from the tip speed ratio versus power coefficient graph. After the observation, it is seen that the optimum value for the chord length is 0.4 meters.

3.11. Number of Blades

Increasing the number of blades can potentially increase the power output of the VAWT. This is because more blades can capture a greater amount of wind energy, especially at lower wind speeds. However, there is an optimum number of blades that balances power generation and other factors such as drag and interference effects. (Manwell, McGowan, and Rogers, 2019)

Here, the effects of different blade numbers on the wind turbine will be examined. At the same time, the best number of blades for the wind turbine will be obtained. In the analysis of the number of blades, the graph of the tip speed ratio - power coefficient will be used.

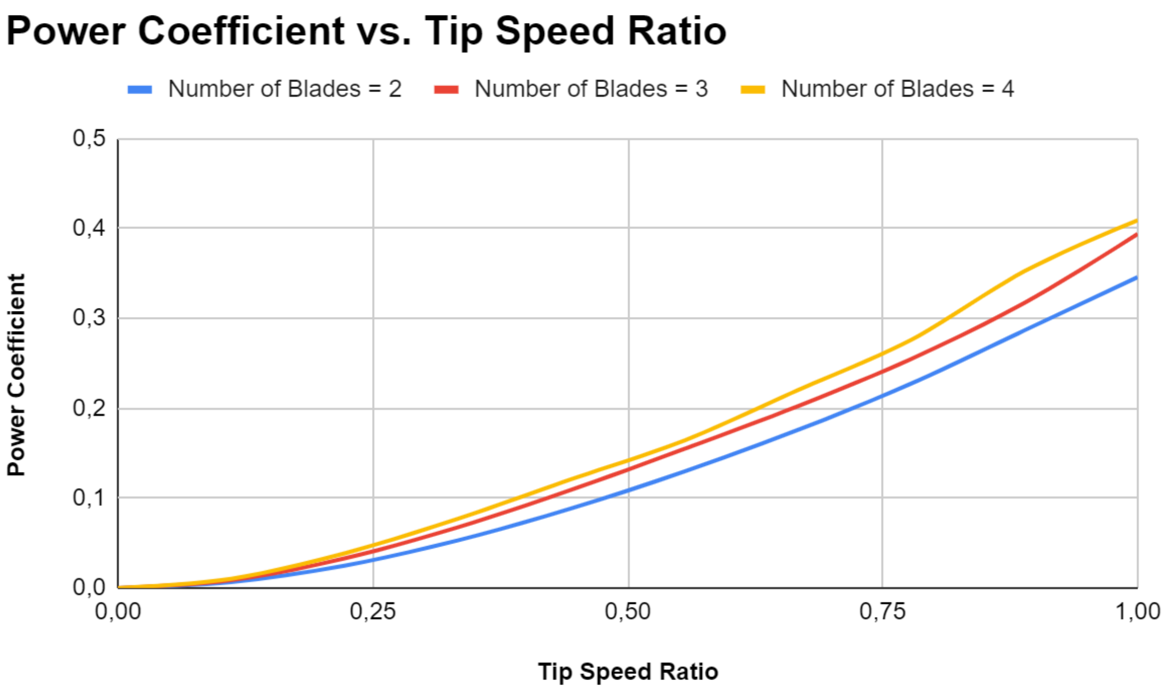


Figure 10: Blades number comparison between 2, 3, and 4.

The number of blades may be within a certain range for the wind turbine at hand. The values in this value range are examined one by one and the most efficient value for the wind turbine is obtained from the tip speed ratio versus power coefficient graph. After the observation, it is seen that the optimum value for the number of blades is 4.

3.12. Initial Angle of Attack

. The initial angle of attack affects the lift and drag characteristics of the rotor blades. By optimizing the angle of attack, it is possible to achieve higher lift and lower drag, resulting in improved aerodynamic efficiency of the VAWT. This can lead to increased power output and overall performance.

Here, the effects of different initial angles of attack on the wind turbine will be examined. At the same time, the best initial angle of attack for the wind turbine will be obtained. In the analysis of the initial angle of attack, the tip speed ratio versus power coefficient graph will be used.

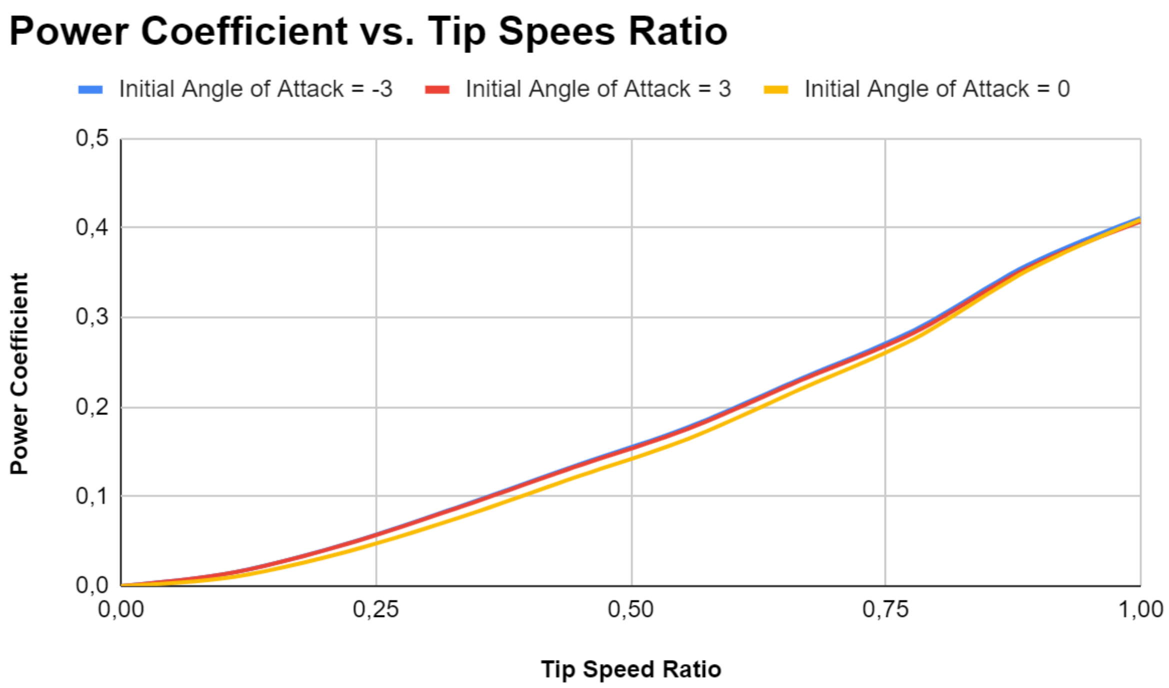


Figure 11: Initial angle of attack comparison between 0, 3, and -3 degrees

The initial angle of attack may be within a certain range for the wind turbine at hand. The values in this value range are examined one by one and the most efficient value for the wind turbine is obtained from the tip speed ratio versus power coefficient graph. After the observation, it is seen that the optimum value for the initial angle of attack is -3 degree.

In the above sections, the necessary optimization processes were carried out for the wind turbine. The most efficient values were obtained for each design parameter. These values are;

Table 3. 3 Final values of the turbine parameters after the optimization process

Symbol	Parameter	Value
V_0	Air Speed	4.72 m/s
R	Rotor Radius	0.50 m
c	Blade Chord	0.40 m
L	Blade Length	2.00 m
N	Number of Blades	4
α_0	Initial Angle of Attack	-3°

3.13. Results

In this section, the graphs of values such as torque, power coefficient, angle of attack with tip speed ratio will be shown in order to better understand the wind turbine. These graphs and parameters show that we can gain deeper insights into the operation of the wind turbine.

RPM

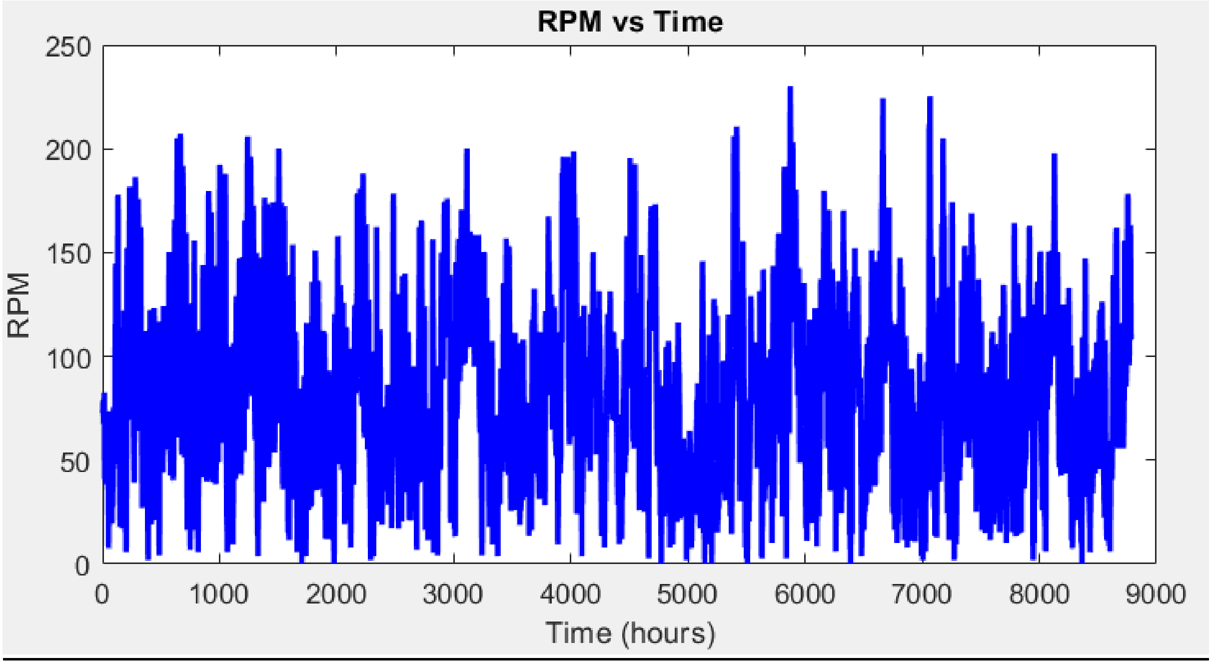


Figure 12: RPM vs. Time

<u>Average Torque</u>

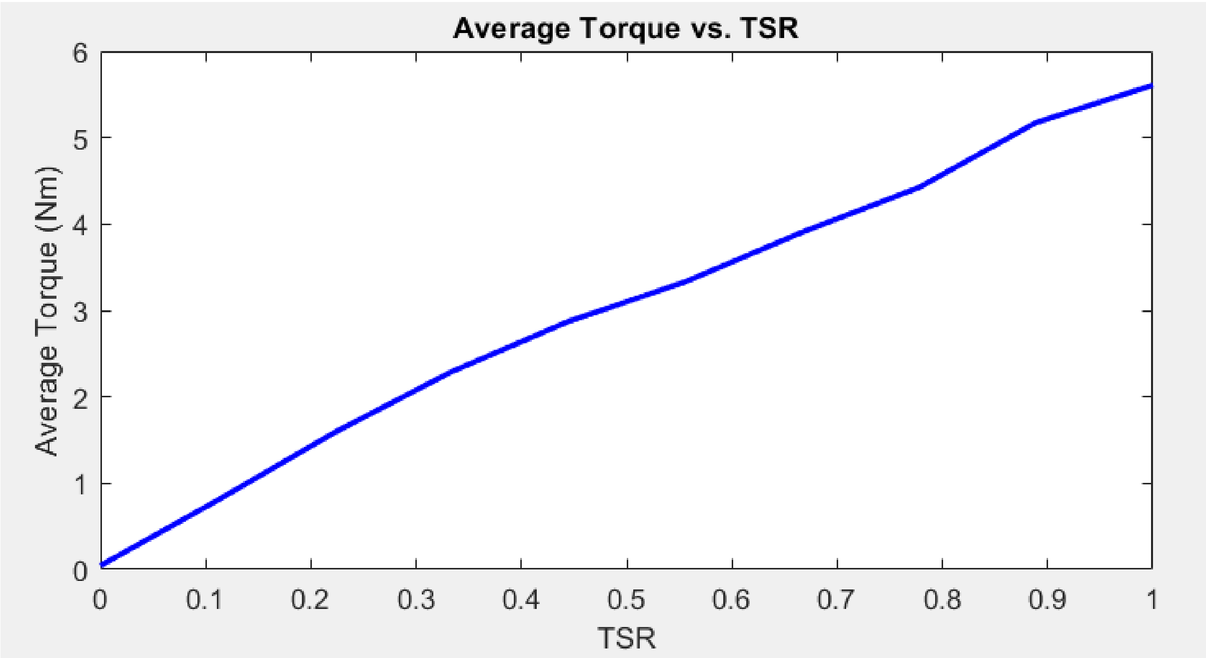


Figure 13: Average torque vs. TSR

Average torque value is 3.0033 Nm determined by matlab.

Power Coefficient

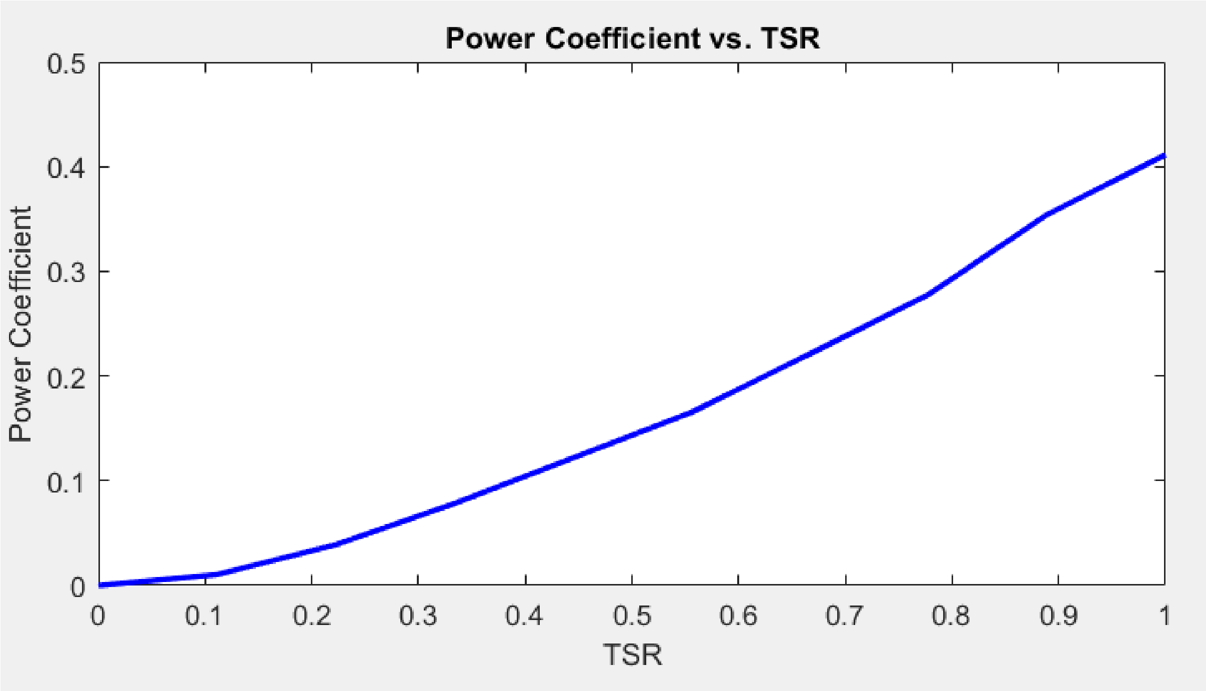


Figure 14: Power Coefficient vs. TSR

3.14. Analysis of Ansys(CFX) Results

The Ansys (CFX) simulations provided valuable insights into the aerodynamic performance of the VAWT. It showed the flow of wind around the blades, the formation of vortices, and the variation of pressure and velocity across the turbine.

The torque on the rotor was accurately predicted by the CFX model. These results helped in understanding the performance of the turbine and in identifying areas for design improvement.

Furthermore, the ansys simulations demonstrated that the designed VAWT could effectively harness wind from all directions. This was due to the vertical arrangement of the blades, which captured the wind irrespective of its direction.

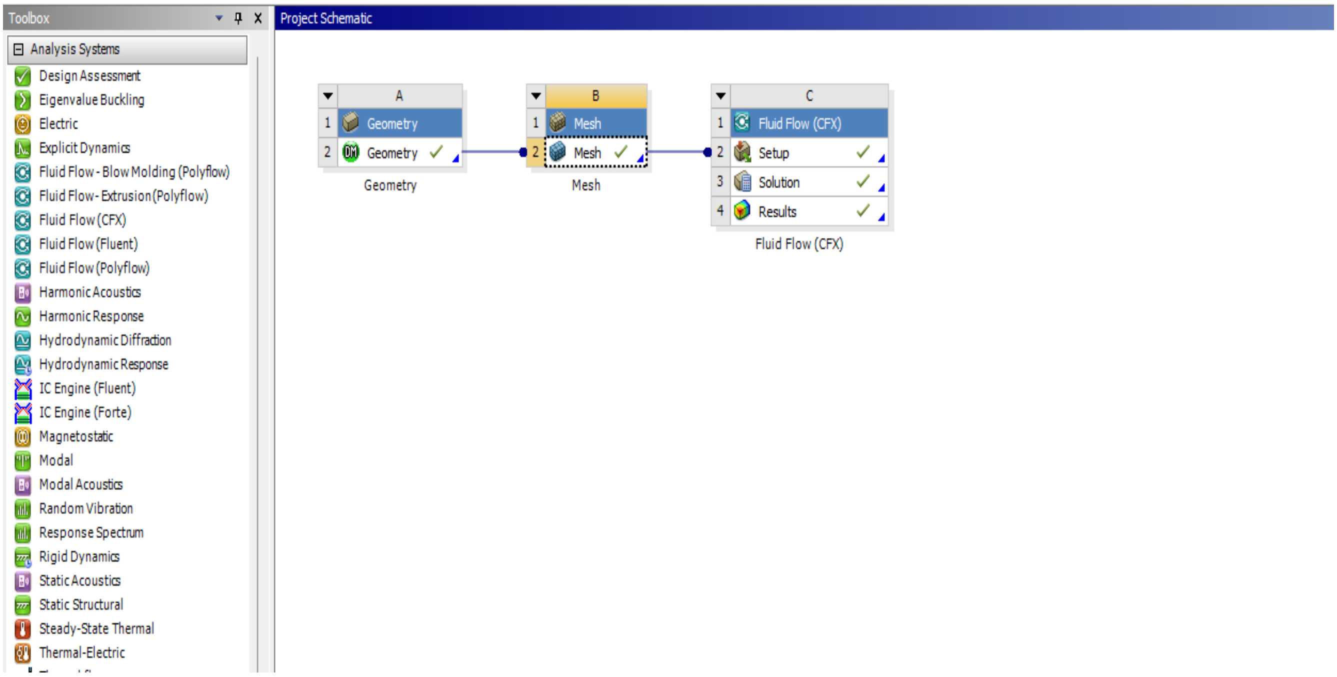


Figure 15: Ansys Project Schematic

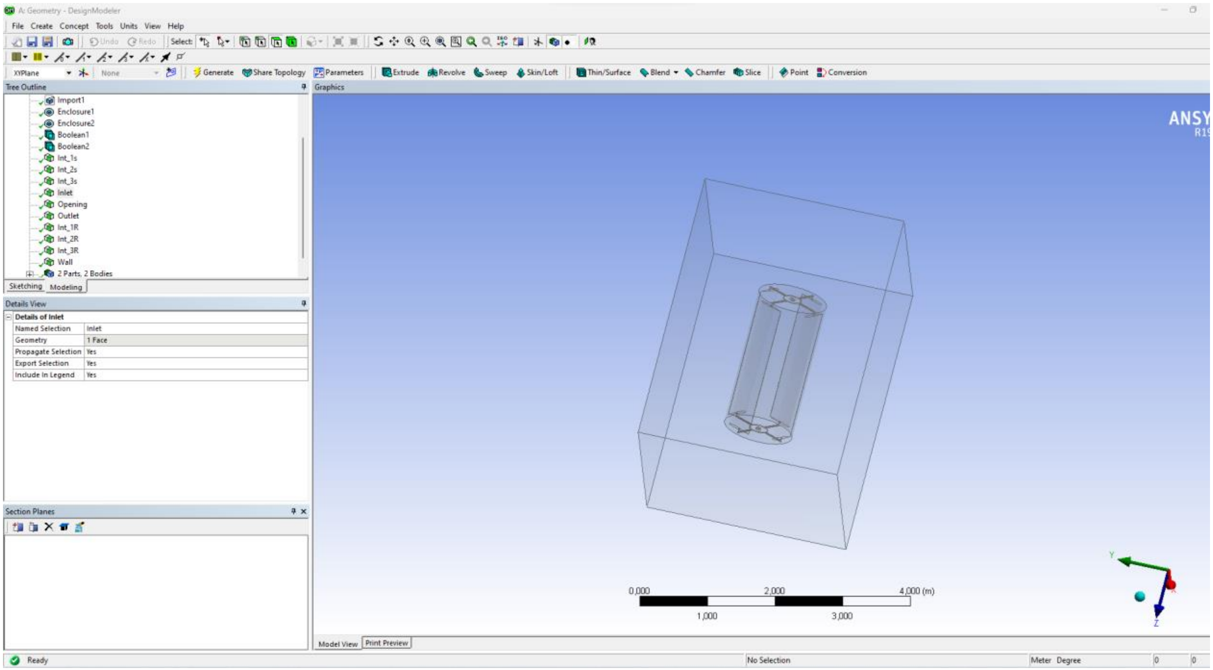


Figure 16: Ansys Geometry

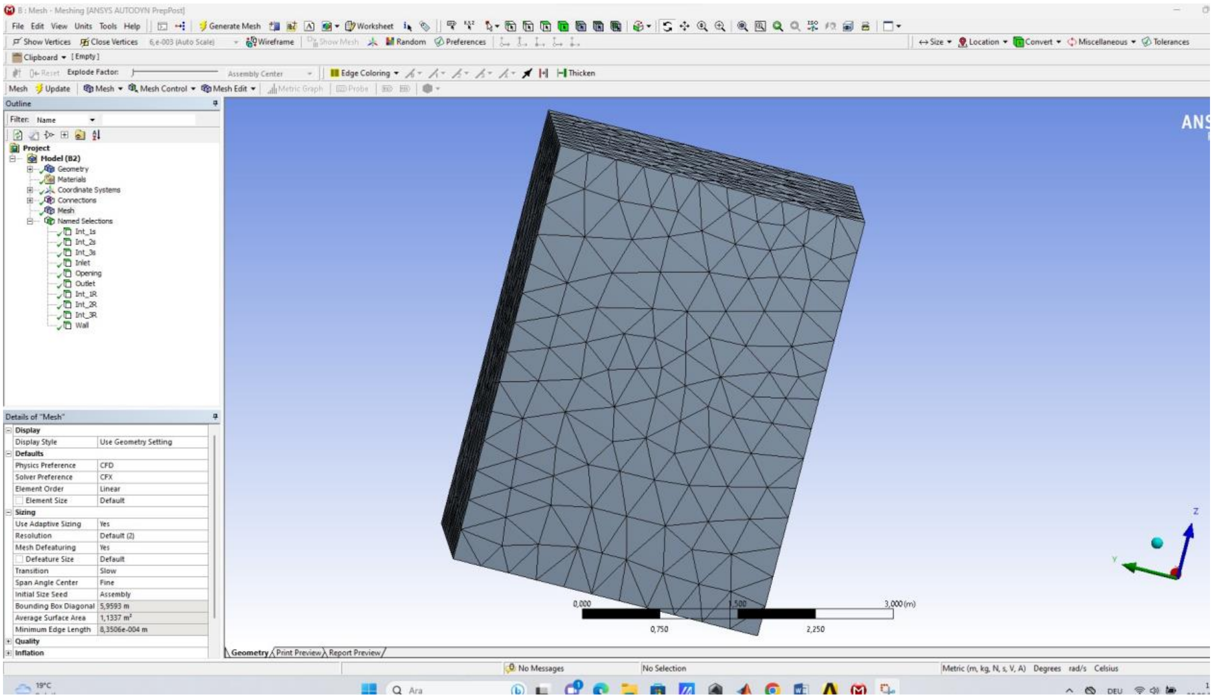


Figure 17: MESH

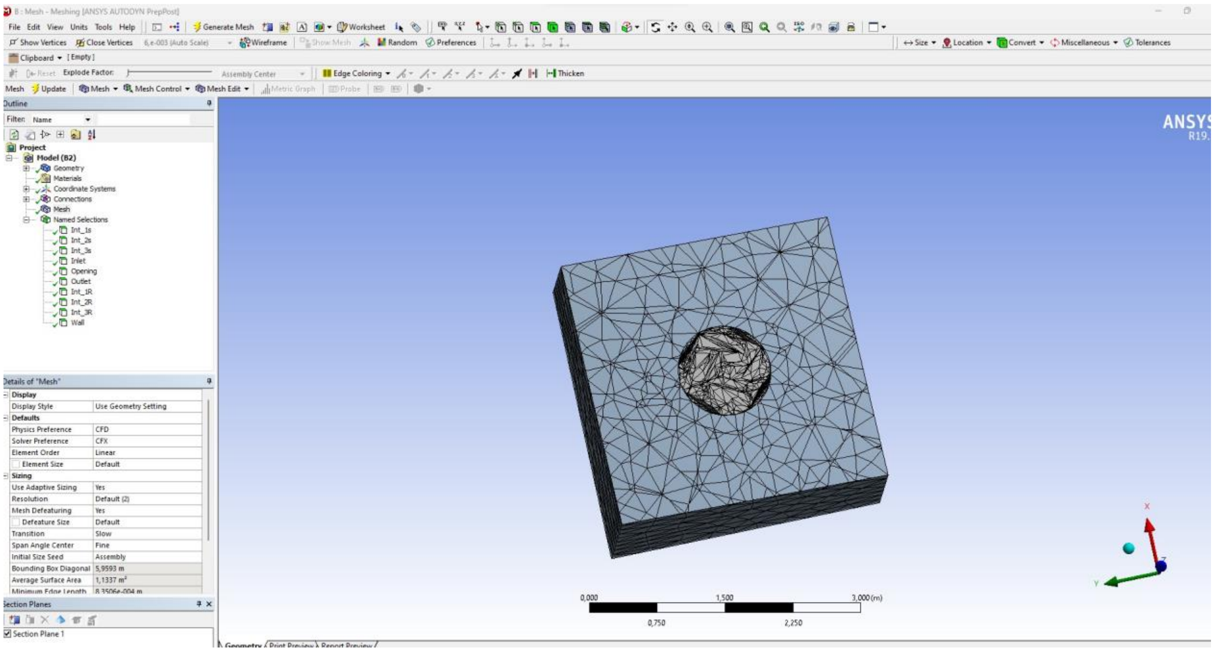


Figure 18: MESH-II

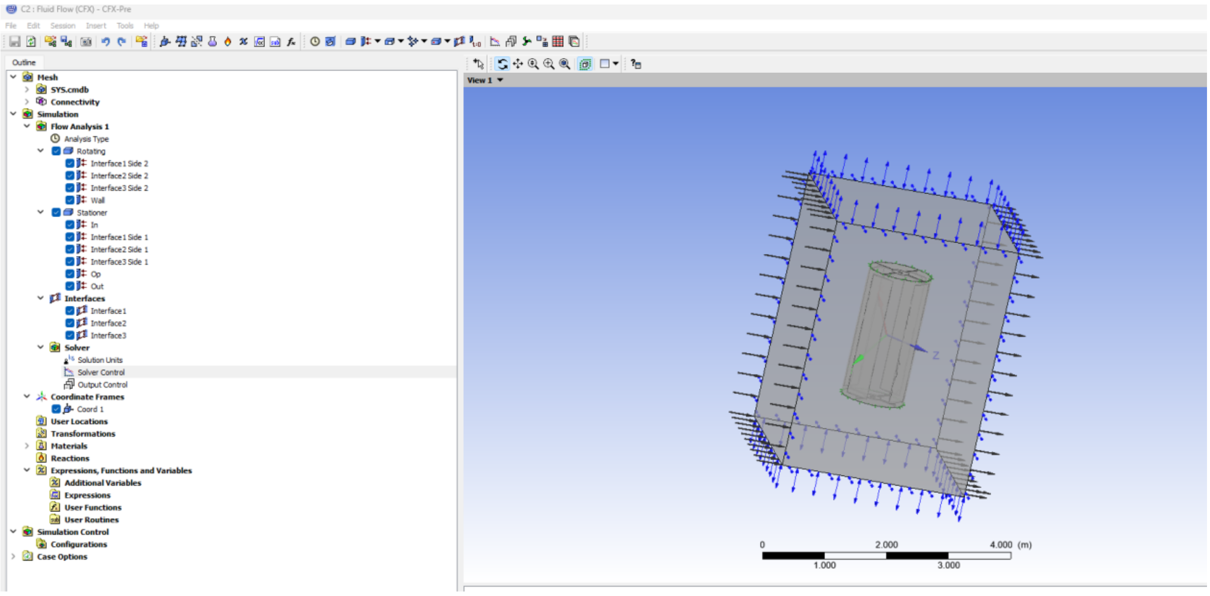


Figure 19: CFX Set-up

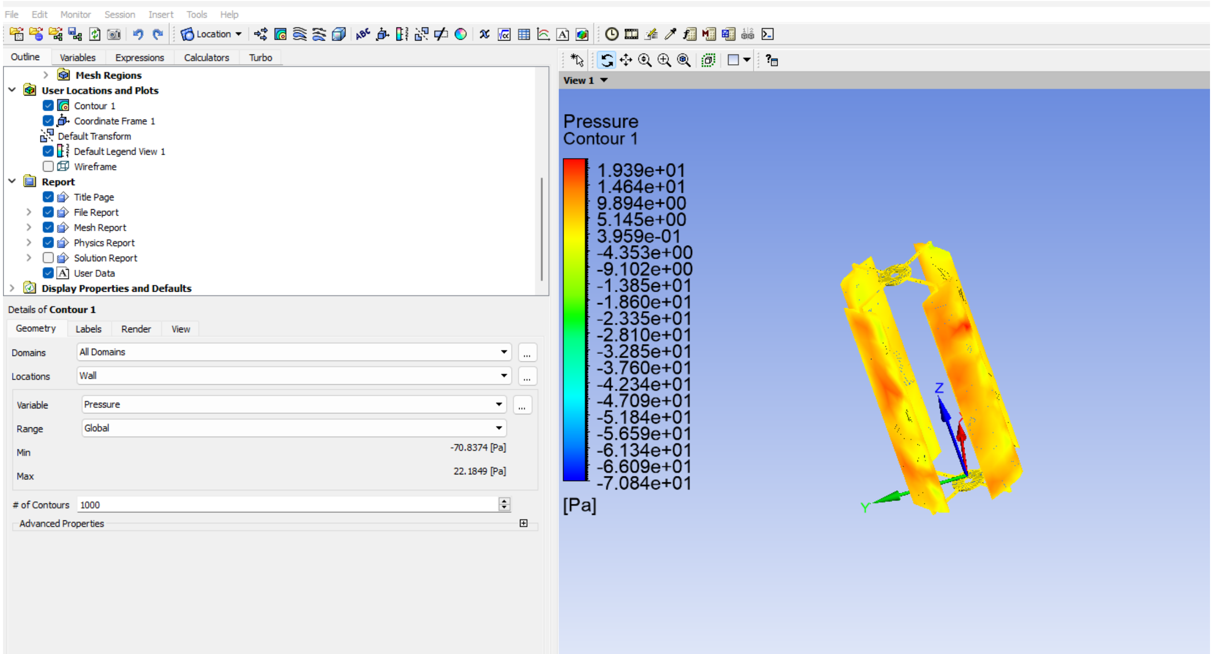


Figure 20: Results of pressure

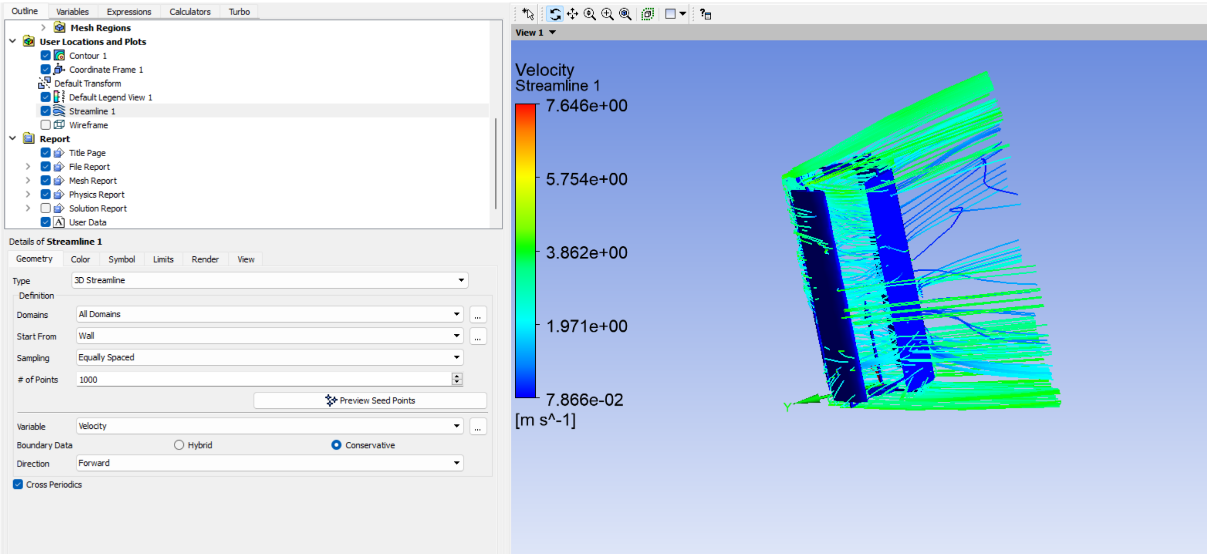


Figure 21: Results of Velocity

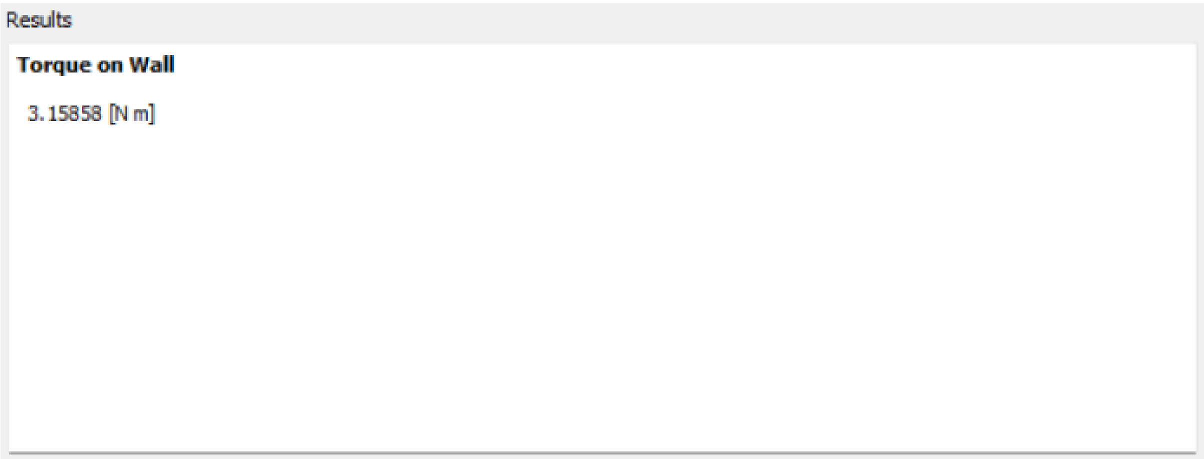


Figure 22: Torque Result

3.15. Comparing The Results

For our wind turbine, aerodynamic analysis of the same dimensions and wind speed were carried out using both matlab and ansys programs. The average torque value obtained from the Matlab program is 3.0033 Nm. The average torque value obtained from the Ansys program is 3.15858 Nm. The average torque values obtained from these two programs give similar results. From here, we can understand that we have designed our wind turbine correctly both for matlab and for the ANSYS program.

3.16. Type of Generators

3.16.1. Permanent magnet synchronous generators

The type of generator that uses permanent magnets is referred to as synchronous because the rotor and the magnetic field rotate with the same speed. Synchronous generators typically have a high power density and low mass, that is why they are increasingly used in wind turbine applications. Challenges imposed by these generators is that under extreme heat development, the permanent magnets can demagnetize, making the generator useless, and that they cannot produce electricity with a fixed frequency. This is because of the variability of the wind speeds and the same-speed rotation. Therefore, these generators require rectifying power converters. (luvside.de, 2023)

3.16.2. Asynchronous generators

The counterpart to synchronous are asynchronous generators. They create an electric field not using permanent magnets but using extra coils. Faraday's law suggests that an electric current and a magnetic field always exist together. This allows us to use a magnetic field to induce an electric current in the way that is detailed here, but it also helps us to create a magnetic field by sending a current through a coil. This is exactly what asynchronous generators do. This kind of generator therefore needs a power supply specifically for the magnets, but it is less prone to damage and might be more reliable than its counterpart. Moreover, it has a higher degree of damping so that it can absorb rotor speed fluctuations much more easily. (luvside.de, 2023)

3.17. Generator Selection

RPM values are calculated for vertical axis wind turbine;

Minimum RPM of the vertical axis wind turbine calculated from matlab is 38.19.

Maximum RPM of the vertical axis wind turbine calculated from matlab is 225.53.

Average RPM of the vertical axis wind turbine calculated from matlab is 90.11.

Also, the hourly RPM graph was shown before.

Average Torque of the vertical axis wind turbine calculated from matlab is 3 Nm.

According to these results, we selected the G400M-800-80 Permanent Magnet Generator. Price of this generator is $190. (https://tr.aliexpress.com/item/32947093503.html?gatewayAdapt=glo2tur)

Model	Power (W)		Speed	FRQ	Torque(N · m)	
	Nominal	Max	RPM	Hz	Starting	Nominal
G400M-800-80	**400W**	**440**	**600**	**70**	**<0.1**	**5**

3.18. Produced Energy

In physics, the formula for electrical energy is Energy = Power x Time. Power is typically given in Watts (like a light bulb), time is usually given in seconds, and energy is usually measured in joules. (study.com, 2023)

$$E = Power * Time$$

The best overall formula for the power derived from a wind turbine (in Watts) is $P = 0.5 * Cp * \rho * \pi * L^2 * V^3$, where Cp is the coefficient of performance (efficiency factor, in percent), ρ is air density (in kg/m3), L is the blade length (in meters) and V is the wind speed (in meters per second). (thundersaidenergy.com, 2023)

$$P = 0.5 * Cp * \rho * \pi * L^2 * V^3, \qquad (3.25)$$

Average Power is 135.68 W and maximum power is 332.49 W. These values were determined from matlab code.

Table 3.4- Produced Energy with different times

Time	Produced Energy
Daily	3.26 kWh
Monthly	97 KWh
Yearly	1.17 MWh

The amount of energy produced was calculated according to the specified times and shown in the table.

To find the wind turbine power, simply multiply the efficiency by the wind power available:

$$P_{output} = \mu * P_{avg,wind}$$

μ = 40%

$$P_{output} = 0.4 * (135.68W) = 54.27W$$

$$E = P_{output} * (24h/day) * (365day) = 475.42kWh\ (per\ year)$$

Income from this turbine is;

$$revenue = tariff * Energy$$

Average electricity price in Turkey is 0.181 USD per kWh. (energ

$$revenue = 0.181\$/kWh * 475.42kWh = 86.05\$\ (per\ year)$$

4. COST ANALYSIS

Manufacturing Cost

Part	Material	Cost
Blades	HDPE	$ 8,80
Structural Components	steel-aluminum alloy	$ 32,50
Bearings & Seals	stainless steel & bronze	$ 5,00
Generator	-	$ 190,00
		$ 236,30

	Amount	Income	
Produced Energy	475.42kWh (per year)	$ 86,05	(per year)

In this analysis, the cost of maintenance and installation are ignored.

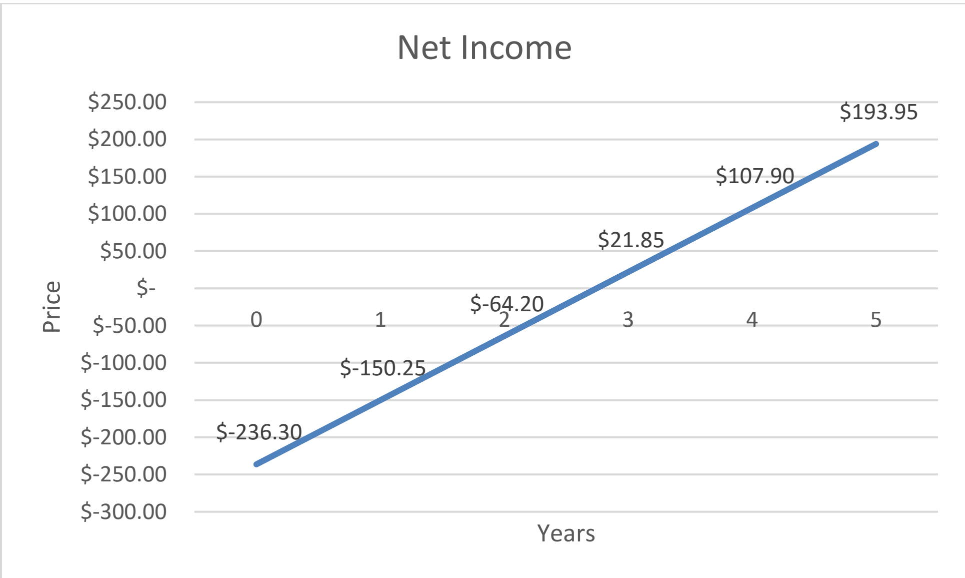


Figure 23: Net Income v Years

According to the table above, this VAWT has paid its expenses since the 3rd year and started to make a profit.

5. CONCLUSION

The designed VAWT exhibited strong performance characteristics, including the ability to harness wind from all directions and operate effectively at a range of wind speeds. The chosen materials for construction proved robust and durable, enhancing the turbine's lifespan and operational efficiency. Ansys modeling allowed for a detailed understanding of the aerodynamics of the turbine, highlighting areas of improvement in design and operation.

From an economic perspective, the analysis showed that the turbine is cost-effective, offering a reasonable payback period on initial investment. Despite the challenges encountered in real-world performance analysis and economic calculations, the project demonstrated the feasibility and viability of VAWTs.

The results of this study also indicate that VAWTs can be a feasible option in areas where wind direction varies significantly, broadening their potential applications. This could be particularly important for remote or off-grid locations, where traditional energy sources may not be readily available or cost-effective.

In conclusion, this study has advanced our understanding of VAWTs, highlighting their potential for efficient wind energy generation. It is hoped that these findings will stimulate further research and innovation in this important field.

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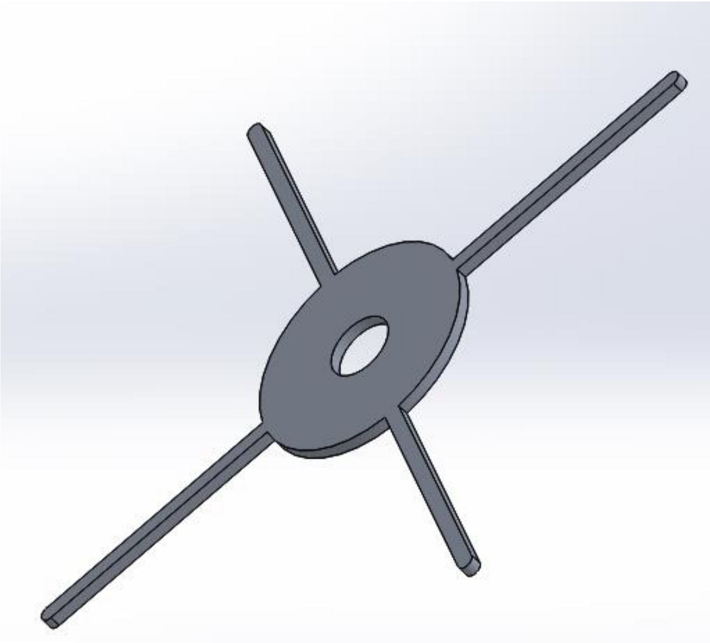
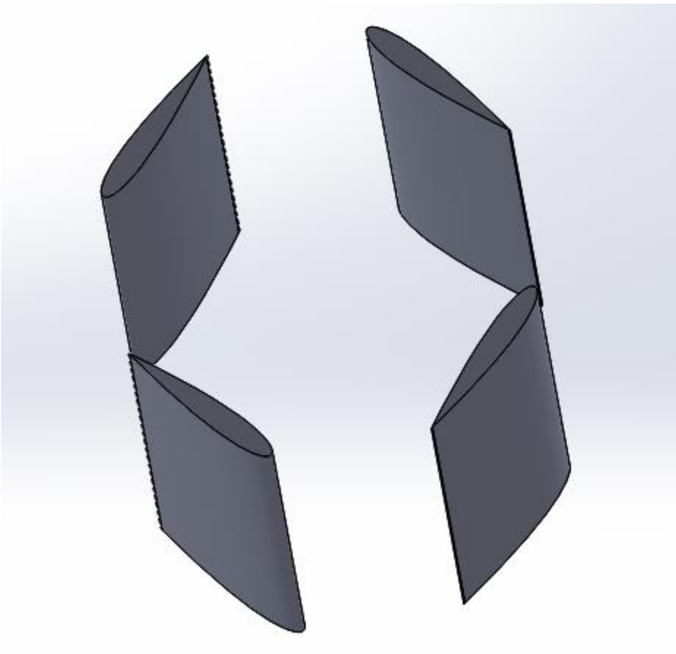
7. APPENDICES

7.1. Vertical Axis Wind Turbine Solidworks Drawings

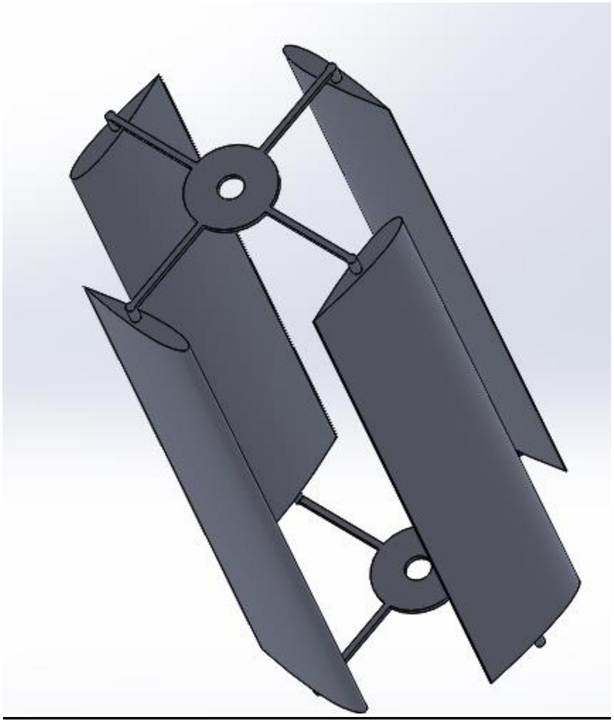
Connecting Rod



Blades

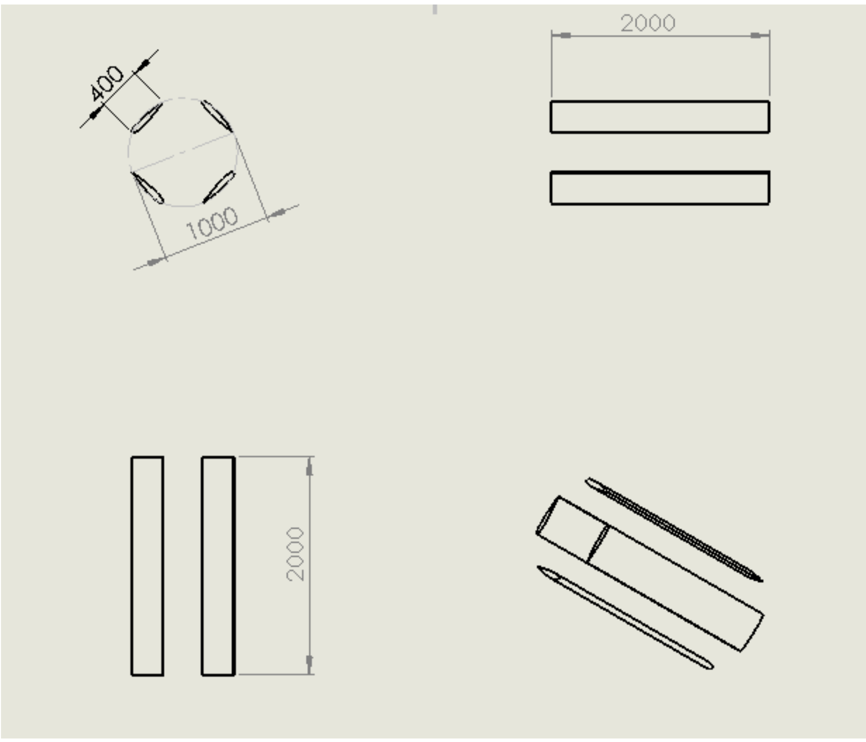


Assembly

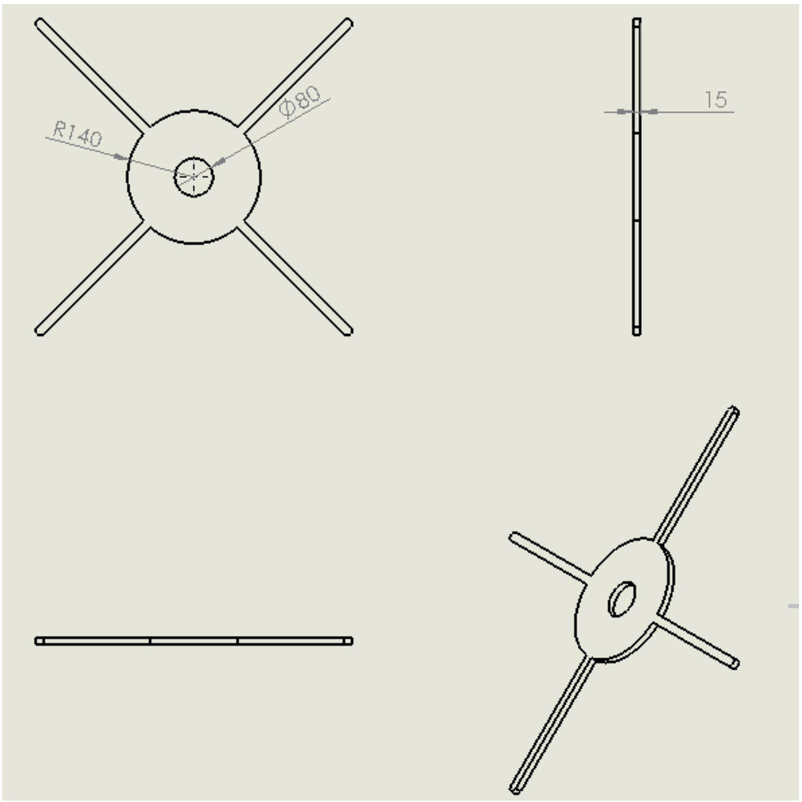


7.2. Technical Drawings

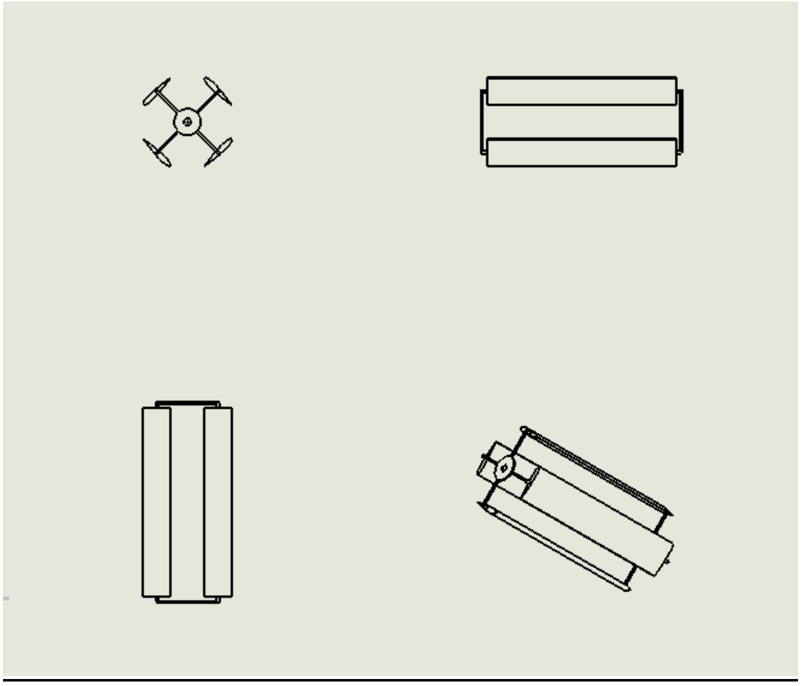
Blades



Connecting Rod



Assembly



7.3. Matlab Code

```
clear

clc

% Specify the file name and sheet name of the Excel file

filename = 'Matlab_veri.xlsx';

sheetname = 'Sayfa1';

% Read the wind speed values from the Excel file

wind_speed_data = xlsread(filename, sheetname);

% Filter the wind speed values between 2 m/s and 12 m/s

filtered_wind_speed = wind_speed_data(wind_speed_data >= 7.2 &
wind_speed_data <= 43.2);

% Calculate the average of the filtered wind speed values
```

```
average_wind_speed = mean(filtered_wind_speed) * 1000 / 3600;

% Constants

rho = 1.225; % Air density (kg/m^3)

R = 0.5; % Rotor radius (m)

N = 4; % Number of blades

c = 0.4; % Blade chord length (m)

L = 2; % Blade length (m)

V_wind = average_wind_speed;% Wind speed (m/s)

TSR = linspace(0, 1, 10); % Tip Speed Ratio

omega = TSR * V_wind / R; % Angular speed (rad/s)

mu = 1.48e-5; % Kinematic viscosity of air (m^2/s)

au_init = 1.01; % Initial upstream velocity induction factor

ad_init = 1.01; % Initial downstream velocity induction factor

epsilon = 1e-3; % Convergence criteria for iterative process

% Define streamtube parameters

n_streamtubes = 10; % Number of streamtubes

theta_upstream = linspace((-89*pi)/180, 89*pi/180, n_streamtubes); %
Angle for upstream streamtubes

theta_downstream = linspace(91*pi/180, 269*pi/180, n_streamtubes); %
Angle for downstream streamtubes

alpha_init = deg2rad(0); % Initial angle of attack (rad)

% Calculate swept area

S = 2 * L * R;

% Preallocate arrays

alpha = zeros(1, n_streamtubes);

Cnu = zeros(1, n_streamtubes);

Ctu = zeros(1, n_streamtubes);

Fnu = zeros(1, n_streamtubes);
```

```
Ftu = zeros(1, n_streamtubes);

Cnd = zeros(1, n_streamtubes);

Ctd = zeros(1, n_streamtubes);

Fnd = zeros(1, n_streamtubes);

Ftd = zeros(1, n_streamtubes);

Cpd = zeros(1, n_streamtubes);

Cpu = zeros(1, n_streamtubes);

Vu = zeros(1,n_streamtubes);

Tup = zeros(1,n_streamtubes);

Auvector = zeros(1,n_streamtubes);

auvector = zeros(1,n_streamtubes);

Wu = zeros(1,n_streamtubes);

costh = zeros(1,n_streamtubes);

cosao = zeros(1,n_streamtubes);

sinth = zeros(1,n_streamtubes);

sinao = zeros(1,n_streamtubes);

Reb = zeros(1,n_streamtubes);

for k = 1 : 10

% Iterate over upstream streamtubes

i = 0;

while (i~=n_streamtubes)

i = i + 1;

au = au_init;

newau = 1;

% Iterative process for upstream induction factor (au)

while (au - newau) > epsilon

au = newau;
```

```
Vu = V_wind * au;

% Local Tip Speed Ratio

X = R * omega(k) / Vu;

% Calculate local resultant air velocity (Wu)

Wu = sqrt(Vu^2 * ((X - (sin(theta_upstream(i)))^2) +
(cos(theta_upstream(i))^2)));

% Calculate local Reynolds number

Reb(i) = rho * Wu * c / mu;

% Calculate angle of attack

costh = cos(theta_upstream(i));

cosao = cos(alpha_init);

sinth = sin(theta_upstream(i));

sinao = sin(alpha_init);

alpha = asin((costh * cosao) - ((X - sinth) * sinao) / (sqrt((X - sinth)^2
+ costh^2)));

if alpha * 180 / pi == 1

Cl = 0.2042;

Cd = 0.01858;

elseif alpha * 180 / pi == 20.7778

Cl = 0.7963;

Cd = 0.01924;

elseif alpha * 180 / pi == 40.5556

Cl = 1.7549;

Cd = 0.07031;

elseif alpha * 180 / pi == 60.3333

Cl = 2.4412;

Cd = 0.13807;

else
```

```
Cl = 0.8155;
Cd = 0.34388;
end
% Calculate normal coefficient (Cn) and tangential coefficient (Ct)
Cnu = Cl * cosd(alpha) + Cd * sind(alpha);
Ctu = Cl * sind(alpha) - Cd * cosd(alpha);
% Calculate the upwind flow conditions using Simpson's rule
g = abs(sec(theta_upstream) .* (Cnu .* cos(theta_upstream) - Ctu .*
sin(theta_upstream)) .* (Wu ./ Vu).^2);
fup = trapz(theta_upstream, g) * N * c / (8 * pi * R);
newau = pi / (fup + pi);
end
% Store angle of attack and au value in vectors
Auvector(i) = alpha;
auvector(i) = newau;
% Calculate force and torque coefficients
Fnu(i) = (c * L / S) * Cnu * (Wu / V_wind)^2; % Normal force coefficient
Ftu(i) = (c * L / S) * Ctu * (Wu / V_wind)^2; % Tangential force
coefficient
% Calculate torque produced in the streamtube
Tup(i) = 0.5 * rho * c * R * L * Cnu * Wu^2;
end
% Calculate average upstream torque (av_Tup)
ts1 = trapz(theta_upstream, Tup);
av_Tup = N * (ts1) / (2 * pi);
% Calculate average torque coefficient
av_Cqu = av_Tup / (0.5 * rho * S * R * V_wind^2);
% Calculate upstream power coefficient (Cpu)
```

```
Cpu = av_Cqu * X;
Cnd = zeros(1, n_streamtubes);
Ctd = zeros(1, n_streamtubes);
Fnd = zeros(1, n_streamtubes);
Ftd = zeros(1, n_streamtubes);
Tdp = zeros(1, n_streamtubes);
Vu = zeros(1, n_streamtubes);
Ve = zeros(1, n_streamtubes);
Vd = zeros(1, n_streamtubes);
alpha = zeros(1, n_streamtubes);
X = zeros(1,n_streamtubes);
Wd = zeros(1,n_streamtubes);
Cd = zeros(1,n_streamtubes);
Cl = zeros(1,n_streamtubes);
Advector = zeros(1,n_streamtubes);
advector = zeros(1,n_streamtubes);
j = n_streamtubes + 1;
flag = 0;
i = 0;
% Iterate over downstream streamtubes
while (j~=1)
j = j - 1;
i = i + 1;
ad = ad_init; % velocity induction factor upstream
newad = auvector(j); % initialize, ad must be different from newad
% Iterative process for downstream induction factor (ad)
while (ad - newad) > epsilon
```

```
ad = newad;

Ve = V_wind * (2 * auvector(j) - 1);

Vd = Ve * ad;

% Local Tip Speed Ratio

X = R * omega(k) / Vd;

% Calculate local resultant air velocity (Wd)

Wd = sqrt(Vd^2 * ((X - (sin(theta_downstream(i)))^2) +
(cos(theta_downstream(i))^2)));

% Calculate local Reynolds number

Reb(i) = rho * Wd * c / mu;

% Calculate angle of attack

costh = cos(theta_downstream(i));

cosao = cos(alpha_init);

sinth = sin(theta_downstream(i));

sinao = sin(alpha_init);

alpha = asin(costh * cosao - (X - sinth) * sinao / sqrt(((X - sinth)^2)
+ (costh^2)));

neg = 0;

if (sign(alpha)==-1)

neg = 1;

end

if alpha * 180 / pi == 1

Cl = 0.2270;

Cd = 0.01952;

elseif alpha * 180 / pi == 20.7778

Cl = 0.7692;

Cd = 0.02146;

elseif alpha * 180 / pi == 40.5556
```

```
Cl = 2.3154;

Cd = 0.02943;

elseif alpha * 180 / pi == 60.3333

Cl = 2.8719;

Cd = 0.05268;

else

Cl = 0.8598;

Cd = 0.23233;

end

% Calculate normal coefficient (Cn) and tangential coefficient (Ct)

Cnd = (Cl * cosd(alpha)) + (Cd * sind(alpha));

Ctd = (Cl * sind(alpha)) - (Cd * cosd(alpha));

% Calculate the integral using Simpson's rule

g = abs(sec(theta_downstream) .* (Cnd .* cos(theta_downstream) - Ctd .*
sin(theta_downstream)) .* (Wd ./ Vd).^2);

fdw = trapz(theta_downstream, g) * N * c / (8 * pi * R);

if (flag ==0)

newad = pi/(fdw+pi);

end

if (newad<0.01)

warning('newad<0.01 at theta = %d and alpha = %d',
(theta_downstream(i)*180/pi));

if (i>1)

newad = advector(i-1);

else

newad = auvector (i);

end

flag = 1;
```

```
end

end

% Store angle of attack and ad value in vectors

Advector(i) = alpha;

advector(i) = newad;

% Calculate force and torque coefficients

Fnd(i) = (c * L / S) * Cnd * (Wd / V_wind)^2; % Normal force coefficient

Ftd(i) = (c * L / S) * Ctd * (Wd / V_wind)^2; % Tangential force
coefficient

% Calculate torque produced in the streamtube

Tdp(i) = 0.5 * rho * c * R * L * Cnd * Wd^2;

end

% Calculate average downstream torque (av_Tdp)

ts2 = trapz(theta_downstream, Tdp);

av_Tdp = N * (ts2) / (2 * pi);

% Calculate average torque coefficient

av_Cqd = av_Tdp / (0.5 * rho * S * R * V_wind^2);

% Calculate downstream power coefficient (Cpd)

Cpd = av_Cqd * X;

Cpt(k) = Cpd + Cpu;

av_t(k) = av_Tup + av_Tdp;

end

% Calculate RPM

RPM = ( wind_speed_data * 1000 * 60 / 3600 ) / ( 2 * pi * R);

% Calculate minimum RPM

RPM_min = ( min(filtered_wind_speed) * 1000 * 60 / 3600 ) / ( 2 * pi *
R);

% Calculate maksimum RPM
```

```
RPM_max = ( max(filtered_wind_speed) * 1000 * 60 / 3600 ) / ( 2 * pi *
R);

% Calculate average RPM

RPM_avg = ( V_wind * 60 ) / ( 2 * pi * R);

% Calculate average torque

average_torque = mean(av_t);

% Calculate Power Output

Power_output = 0.5 * Cpt * rho * pi * L^2 * V_wind^3; % Watt

% Average Power Output

average_power_output = mean(Power_output); % Watt

% Maximum power output ( power rating )

Power_output_max = max(Power_output);

%% Plotting

figure;

subplot(2, 2, 1);

plot(theta_upstream * 180 / pi, auvector, 'r', 'LineWidth', 2);

xlabel('Theta (degrees)');

ylabel('Upstream induction factor (au)');

title('Upstream Induction Factor Distribution');

subplot(2, 2, 2);

plot(theta_downstream * 180 / pi, advector, 'b', 'LineWidth', 2);

xlabel('Theta (degrees)');

ylabel('Downstream induction factor (ad)');

title('Downstream Induction Factor Distribution');

subplot(2, 2, 3);

plot(theta_upstream * 180 / pi, Auvector * 180 / pi, 'r', 'LineWidth',
2);

xlabel('Theta (degrees)');
```

```
ylabel('Angle of Attack (degrees)');

title('Upstream Angle of Attack Distribution');

subplot(2, 2, 4);

plot(theta_downstream * 180 / pi, Advector * 180 / pi, 'b', 'LineWidth',
2);

xlabel('Theta (degrees)');

ylabel('Angle of Attack (degrees)');

title('Downstream Angle of Attack Distribution');

figure;

subplot(2, 2, 1);

plot(theta_upstream * 180 / pi, Fnu, 'r', 'LineWidth', 2);

xlabel('Theta (degrees)');

ylabel('Normal Force Coefficient (Cn)');

title('Upstream Normal Force Coefficient Distribution');

subplot(2, 2, 2);

plot(theta_upstream * 180 / pi, Ftu, 'b', 'LineWidth', 2);

xlabel('Theta (degrees)');

ylabel('Tangential Force Coefficient (Ct)');

title('Upstream Tangential Force Coefficient Distribution');

subplot(2, 2, 3);

plot(theta_downstream * 180 / pi, Fnd, 'r', 'LineWidth', 2);

xlabel('Theta (degrees)');

ylabel('Normal Force Coefficient (Cn)');

title('Downstream Normal Force Coefficient Distribution');

subplot(2, 2, 4);

plot(theta_downstream * 180 / pi, Ftd, 'b', 'LineWidth', 2);

xlabel('Theta (degrees)');
```

```
ylabel('Tangential Force Coefficient (Ct)');

title('Downstream Tangential Force Coefficient Distribution');

figure;

subplot(2, 2, 1);

plot(theta_upstream * 180 / pi, Tup, 'r', 'LineWidth', 2);

xlabel('Theta (degrees)');

ylabel('Torque (Nm)');

title('Upstream Torque Distribution');

subplot(2, 2, 2);

plot(theta_downstream * 180 / pi, Tdp, 'b', 'LineWidth', 2);

xlabel('Theta (degrees)');

ylabel('Torque (Nm)');

title('Downstream Torque Distribution');

subplot(2, 2, 3);

plot(theta_upstream .* 180 / pi, av_t .* ones(1, n_streamtubes), 'r',
'LineWidth', 2);

xlabel('Theta (degrees)');

ylabel('Torque (Nm)');

title('Average Torque');

subplot(2, 2, 4);

plot(theta_upstream * 180 / pi, av_Cqu * ones(1, n_streamtubes), 'b',
'LineWidth', 2);

xlabel('Theta (degrees)');

ylabel('Torque Coefficient');

title('Average Upstream Torque Coefficient');

figure;

subplot(2, 2, 1);
```

```
plot(theta_downstream * 180 / pi, av_Cqd * ones(1, n_streamtubes), 'b',
'LineWidth', 2);

xlabel('Theta (degrees)');

ylabel('Torque Coefficient');

title('Average Downstream Torque Coefficient');

subplot(2, 2, 2);

plot(TSR, Cpt, 'b', 'LineWidth', 2);

xlabel('TSR');

ylabel('Power Coefficient');

title('Power Coefficient vs. TSR');

subplot(2, 2, 3);

plot(TSR, av_t, 'b', 'LineWidth', 2);

xlabel('TSR');

ylabel('Average Torque (Nm)');

title('Average Torque vs. TSR');

subplot(2, 2, 4);

plot(RPM, 'b', 'LineWidth', 2);

xlabel('Time (hours)');

ylabel('RPM');

title('RPM vs Time');
```