MARMARA UNIVERSITY

FACULTY OF ENGINEERING

SITE SPECIFIC DESIGN CONSIDERATIONS FOR VERTICAL AXIS WIND TURBINES INCLUDING AEROELASTIC EFFECTS

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MARMARA UNIVERSITY

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by

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January, 2022 Cihan DURMİŞ,Mücahit Mustafa USTA

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ABSTRACT

SITE SPECIFIC DESIGN CONSIDERATIONS FOR VERTICAL AXIS WIND TURBINES INCLUDING AEROELASTIC EFFECTS

Wind energy is one of the most important renewable energy sources. Wind turbines take kinetic energy from the wind and convert it into mechanical energy. In this study, to design a vertical axis wind turbine suitable for the wind distribution created by using the wind speed data of the region for the newly opened campus of Marmara University. First, we obtained the wind speed distribution in the region with the help of Global Wind Atlas. Then the most suitable weibull probability distribution was found for this wind distribution. As a step, vertical axis wind turbine was chosen as the most suitable wind turbine type for the region. We designed the turbine we chose with the help of SOLIDWORKS. The aim of this study is aerolastic analysis. Aerolastic analyzes of the turbine were performed using QBLADE. The most suitable airfoil was selected. Airfoil analyzes were also performed with QBLADE. Then, structural analyzes were made using SOLIDWORKS. Finally, the cost and the effects of this wind turbine we designed on the environment and nature were analyzed.

SYMBOLS

$\mathbf{A_b}$: surface area of the blade (m^2)

$\mathbf{A_{strut}}$: cross sectional area of strut (m^2)

c : chord length of the blade (m)

$\mathbf{c_s}$: scale factor for weibull distribution

k : shape factor for weibull distribution

n : number of revolutions of the rotor per minute (rpm)

v : wind speed (m/s)

d : shaft diameter

v_m : mean wind speed (m/s)

v_{mp} : most probable wind speed (m/s)

v_{max} : maximum wind speed(m/s)

v_k : kinematic viscosity ($1.67x10^{-5}$ m^2/s)

W : relative velocity of the blade (m/s)

U : upstream air velocity (m/s)

$\mathbf{U_n}$: normal component of the upstream air velocity (m/s)

$\mathbf{U_t}$: tangential component of the upstream air velocity (m/s)

$\mathbf{m_{blade}}$: weigth of the blade (kg)

$\mathbf{m_{strut}}$: weigth of the strut (kg)

g : gravitational acceleration (9.81 m^2/s)

V : tangential velocity of the blade (m/s)

θ : azimuthal position angle of the blade (rad)

α : angle of attack of the blade (rad)

R : radius of the rotor (m)

H : Heigth of the blade (m)

H_{tower} : heigth of the tower (m)

I : moment of inertia

ω : angular velocity of the rotor (rad/s)

C_p : power coefficient

C_d : drag coefficient

C_n : normal coefficient

C_l : lift coefficient

C_t : tangential coefficient

F : resultant force (N)

F_d : drag force (N)

F_n : normal force (N)

F_l : lift force (N)

F_t : tangential force(N)

F_U : distributed load due to wind (N/m)

r_o : outer radius of the tower

r_i : inner radius of the tower

P : power (W)

T : torque (N.m)

M : moment (N.m)

Re : reynolds number

x : distance in x direction (m)

y : distance in y direction (m)

ρ : air density (1.225 kg/m^3)

λ : tip speed ratio

τ : shear stress

$\boldsymbol{\sigma}$: solidty

$\boldsymbol{\sigma}_{\mathbf{bending}}$: bending stress (Pa)

$\boldsymbol{\sigma}_{\mathbf{axial}}$: axial stress (Pa)

$\boldsymbol{\sigma}_{\mathbf{normal}}$: normal stress (Pa)

$\boldsymbol{\sigma}_{\mathbf{von\text{-}mises}}$: von-mises stress (Pa)

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1. INTRODUCTION

The development of humanity is related to how efficiently it uses the resources it has. Many civilizations have learned to use the resources they have efficiently and left other civilizations behind. Today, fossil resources throughout the world have a wide range of use as a tool in life. These fossil asset reserves are not considered sufficient for the future; On the other hand, large-scale advanced technology and education programs in terms of acquisition and education have caused all countries to reconsider their energy programs and to take the necessary measures urgently. The process of collecting the total energy to be taken from start to finish may result from the use of squeezing the energy and benefiting from the use. The term eco-friendly, which has become popular again in recent years, refers to the fact that it is now a necessity to reduce the fossil fuels used especially during energy production, otherwise we will cause irreversible damage to the world. One of the renewable energy sources is wind energy. It is one of the oldest energy sources used since 3000s. Until recent years, wind energy has been used more for pumping water and obtaining electrical energy in rural areas where there is no power line. Of course, the most important one is sailing ships working with wind power. In an environment where economic and environmental concerns are being felt more and more, like wind It is very important to benefit from an energy source as much as possible. Today, it is now in the energy sector as an alternative energy production source. As a matter of fact, the policies followed and the trend in the sector are moving in this direction. Today, it is now in the energy sector as an alternative energy production source. The use of this energy depends on the height of the wind shaft and the systems of the energy production models. On the other hand, due to reasons such as the variable wind speed, the inability to control and transfer to another place, various uncertainties and some problems related to these uncertainties can be experienced in electricity generation with wind energy.The biggest problem of wind energy is that the wind is not constant, it can change constantly. There is no wind measuring device or power plant in the region we have chosen. For this reason, we will have to obtain wind data first. There are important points that affect the energy produced from the wind, such as at what speeds it is concentrated, the intensity of periodic increases or decreases in wind speed. When the articles are examined, there are many studies for the statistical analysis of wind speed. Many of the studies have examined the probability distribution of wind speeds in a certain time interval. Studies and past data show The most suitable probability distribution for wind speeds is the weibull probability distribution.

For this reason, the scale and shape variable weibull distribution of the data we have was chosen based on the similarity of the weibull probability distributions created with different scale and shape values to the wind speed distribution we have.This research is a preliminary investigation, design and cost for a small-scale wind turbine, since the area on the campus where Marmara University has just moved is a bit outside of the city and a place with good wind. Therefore, our aim in the research is to analyze the wind data in the region and then, according to this analysis, small scale wind turbines.Finally, to check whether we have designed the design in reasonable dimensions. And we will examine the feasibility of the windturbine.

2. MATERIALS AND METHODS

2.1 Weather Data and Study Area

It is a land that is at the top of the university area where we plan to place the turbine. This gives us a significant advantage in terms of wind. Since the wind increases as the altitude increases and the cube of the wind is taken in the basic power equation, it can be considered the most important parameter for us.Although the altitude data obtained from the coordinate changes on the land. .When we add a building height of 10-m15 m above the height of the turbine, the average wind speeds of 100 m were chosen as the wind data set for us.To investigate wind speed variability with respect to climate change, hourly wind speed data was used. Hourly wind speed and direction data were taken from Global Wind Atlas.The datas are for the area shown below:

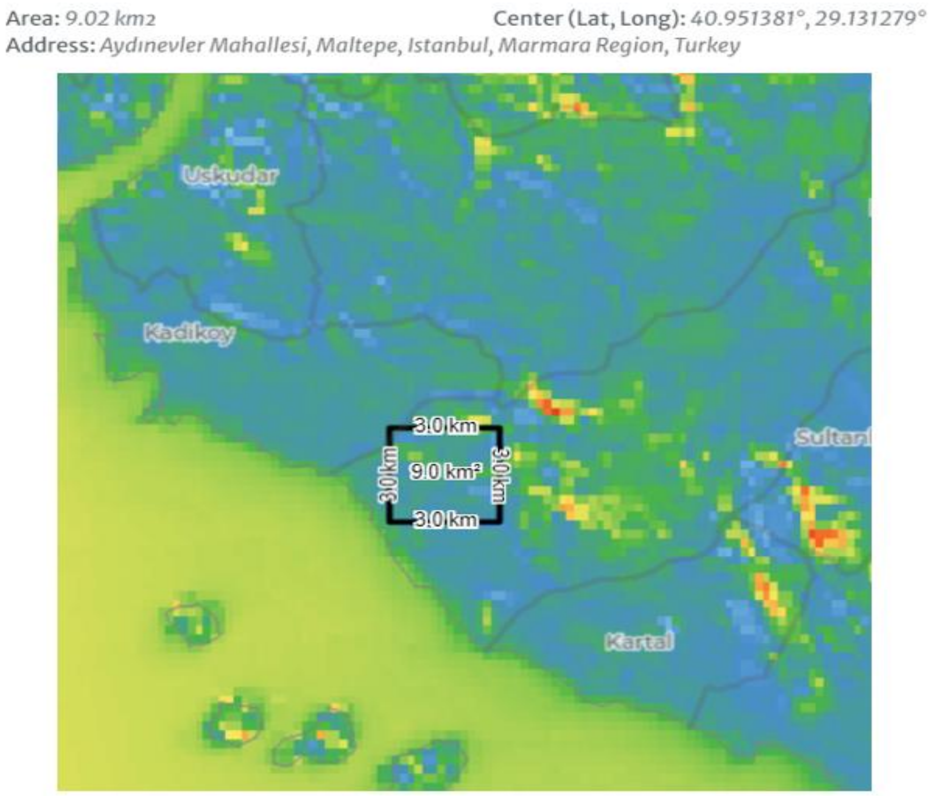


Figure 2.1 Study Area

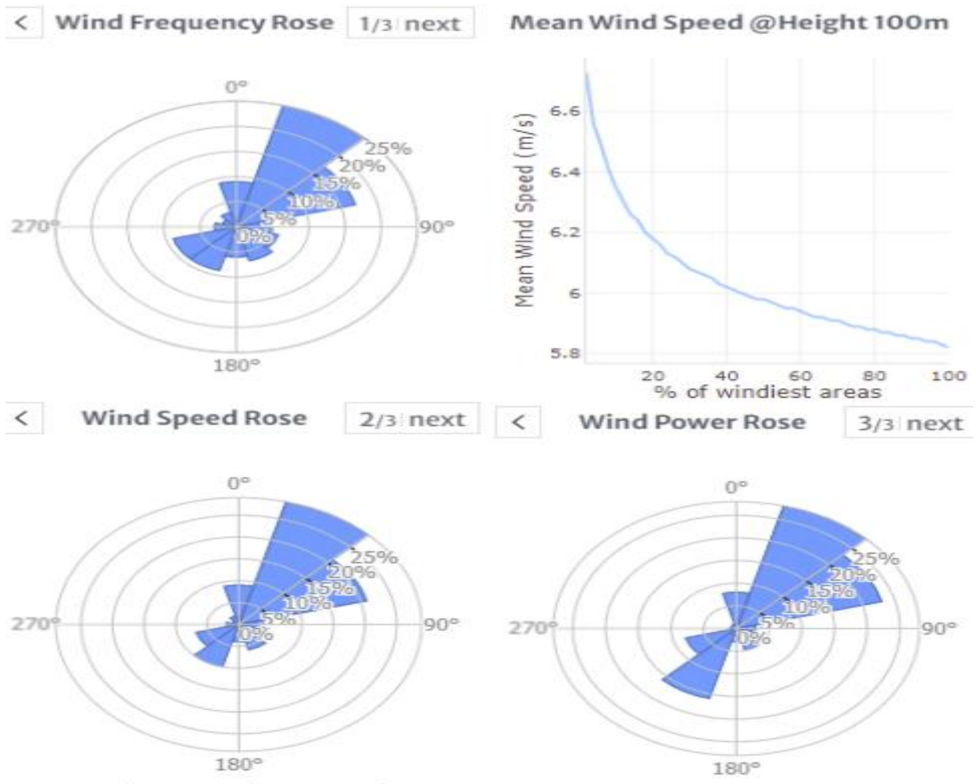


Figure 2.2 Wind frequency,power,and speed rose and Mean Wind Speed Graph

The wind direction is determined by the frequency, speed and power roses we look at. It can be determined that our dominant wind direction is between 10 degrees and 45 degrees.

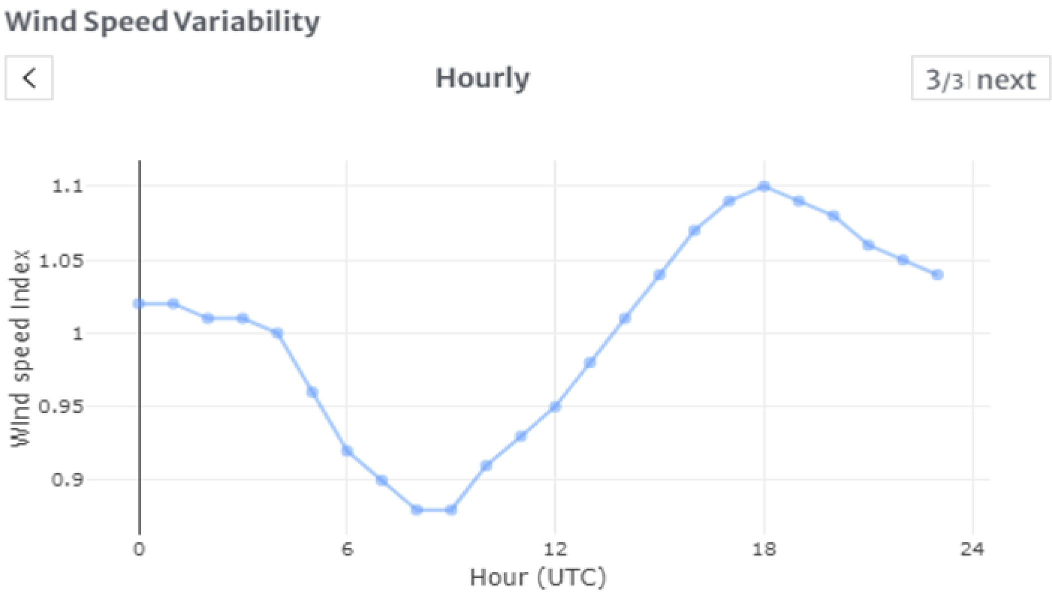


Figure 2.3 Hourly Wind Speed Variability

When we look at the distribution of the hourly wind speed index, our wind speed, which is at the lowest speed between 8:00 and 9:00 in the daytime, reaches its highest average speed towards the evening hours, that is, exactly at 18:00.

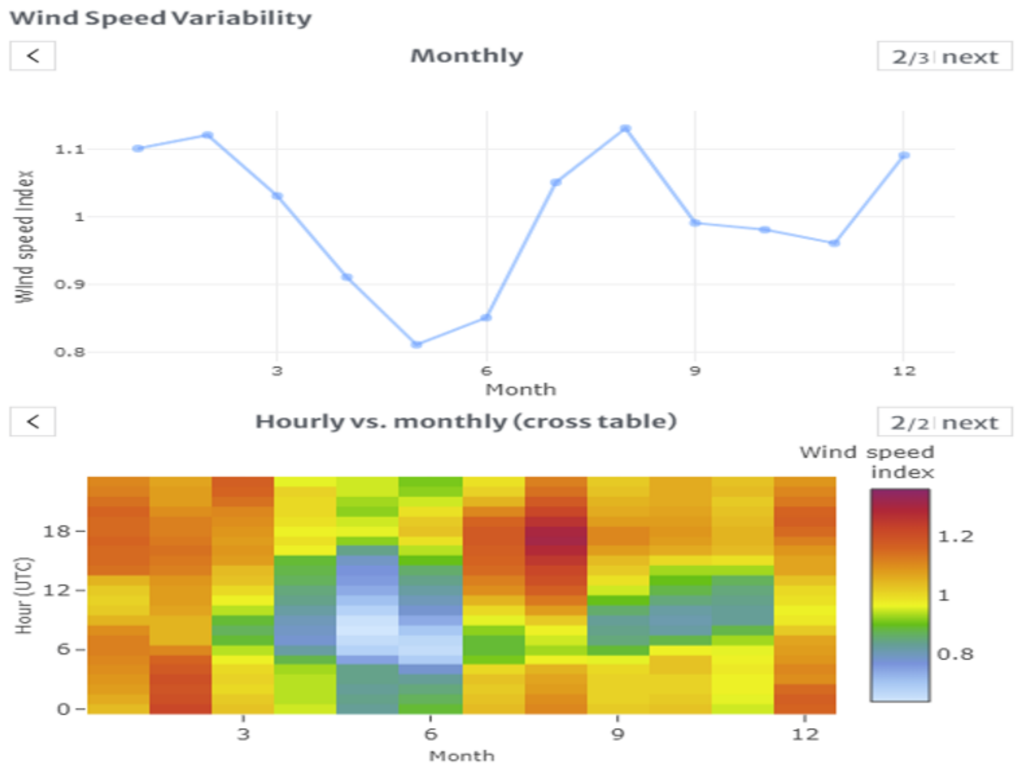


Figure 2.3 Hourly Wind Speed Variability and Hourly vs.monthly(cross table)

When we look at the distribution of the monthly wind speed index, it is seen that the lowest speed in March is the highest average speed in February and August.

The hourly wind speed for every month is calculated by using the data above:

Hour/Month	january	february	March	April	May	June	July	August	September	October	November	December
00:00:00	6.94	7.06	6.50	5.75	5.12	5.24	6.44	7.00	6.12	6.06	6.00	6.81
01:00:00	6.94	7.06	6.50	5.75	5.12	5.24	6.44	7.00	6.12	6.06	6.00	6.81
02:00:00	6.87	6.99	6.43	5.69	5.07	5.19	6.37	6.93	6.06	6.00	5.94	6.74
03:00:00	6.87	6.99	6.43	5.69	5.07	5.19	6.37	6.93	6.06	6.00	5.94	6.74
04:00:00	6.80	6.92	6.37	5.64	5.02	5.14	6.31	6.86	6.00	5.94	5.88	6.68
05:00:00	6.53	6.64	6.12	5.41	4.82	4.93	6.06	6.59	5.76	5.70	5.65	6.41
06:00:00	6.26	6.37	5.86	5.19	4.62	4.73	5.81	6.31	5.52	5.47	5.41	6.14
07:00:00	6.12	6.23	5.73	5.07	4.52	4.63	5.68	6.17	5.40	5.35	5.29	6.01
08:00:00	5.98	6.09	5.61	4.96	4.42	4.52	5.55	6.04	5.28	5.23	5.17	5.88
09:00:00	5.98	6.09	5.61	4.96	4.42	4.52	5.55	6.04	5.28	5.23	5.17	5.88
10:00:00	6.19	6.30	5.80	5.13	4.57	4.68	5.74	6.24	5.46	5.41	5.35	6.08
11:00:00	6.32	6.44	5.92	5.24	4.67	4.78	5.87	6.38	5.58	5.52	5.47	6.21
12:00:00	6.46	6.57	6.05	5.35	4.77	4.88	6.00	6.52	5.70	5.64	5.59	6.34
13:00:00	6.66	6.78	6.24	5.52	4.92	5.04	6.18	6.72	5.88	5.82	5.76	6.54
14:00:00	6.87	6.99	6.43	5.69	5.07	5.19	6.37	6.93	6.06	6.00	5.94	6.74
15:00:00	7.07	7.20	6.63	5.86	5.22	5.35	6.56	7.13	6.24	6.18	6.12	6.94
16:00:00	7.28	7.40	6.82	6.03	5.37	5.50	6.75	7.34	6.42	6.36	6.29	7.14
17:00:00	7.41	7.54	6.94	6.14	5.47	5.60	6.88	7.48	6.54	6.48	6.41	7.28
18:00:00	7.48	7.61	7.01	6.20	5.52	5.65	6.94	7.55	6.60	6.53	6.47	7.35
19:00:00	7.41	7.54	6.94	6.14	5.47	5.60	6.88	7.48	6.54	6.48	6.41	7.28
20:00:00	7.34	7.47	6.88	6.09	5.42	5.55	6.82	7.41	6.48	6.42	6.35	7.21
21:00:00	7.21	7.34	6.75	5.97	5.32	5.45	6.69	7.27	6.36	6.30	6.23	7.08
22:00:00	7.14	7.27	6.69	5.92	5.27	5.40	6.63	7.20	6.30	6.24	6.17	7.01
23:00:00	7.07	7.20	6.63	5.86	5.22	5.35	6.56	7.13	6.24	6.18	6.12	6.94

Table 2.1 Hourly Wind Speed Data per Month

2.1.1 Weibull Distribution

While year-to-year variation in annual mean wind speeds remains hard to predict, wind speedvariations during the year can be well characterised in terms of a probability distribution. TheWeibull distribution has been found to give a good representation of the variation in hourlymean wind speed over a year at many typical sites.

Weibull wind speed probability density function can be represented as:

$$f(v) = \frac{k}{c_s}\left(\frac{v}{c}\right)^{(k-1)} exp\left[-\left(\frac{v}{c_s}\right)^k\right]$$

where f(v) is the probability of observing wind speed v, k is the dimensionless Weibull shape parameter and c is the Weibull scale parameter in m/s. Weibull shape and scale parameters k and c are related with the mean wind speed v_m by the equation:

$$v_m = c_s G\left(1 + \frac{1}{k}\right)$$

where G is the gamma function. After estimating the mean and the variance of the wind speed data,Weibull parameters, c can be calculated by the following approximated equation:

$$c_s = \frac{v_m}{G\left(1+\frac{1}{k}\right)}$$

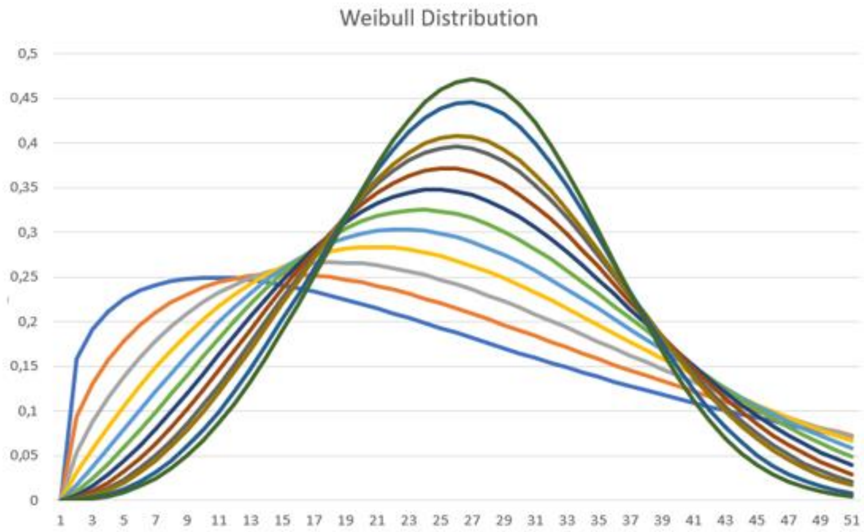
Most probable wind speed' v_{mp} (m/s) defined as the most frequent wind speed for a given wind speed probability distribution function can be computed by

$$v_{mp} = c_s\left(\frac{k-1}{k}\right)^{(1/k)}$$

Wind speed corresponding to the maximum energy' v_{max} (m/s) can be calculated by using the Weibull parameters k and c as follows:

$$v_{max} = c_s\left(\frac{k+2}{k}\right)^{(1/k)}$$

To obtain suitable weibull distribution graph, the average wind speed taken from the atlas is used. The average wind speed was calculated as 6.13 m/s^2. 12 weibull distribution graph are plotted with different shape factors and scale factors which depends on shape factor. All scalce factors are calculated with same average wind speed.



Vm	6.13
k	c
1.3	6.64
1.5	6.79
1.7	6.87
1.9	6.91
2.1	6.92
2.3	6.92
2.5	6.91
2.7	6.89
2.9	6.87
3	6.86
3.3	6.83
3.5	6.81

Figure 2.4 Weibull Distribution Curves

The suitable weibull distribution is the one which fits to the frequency histograph. The histograph shows all the measured wind speed x the frequency from the hourly wind speed table above. The x axis is measured wind speed and the y axis is the frequency data divided by the sum of all frequencies.

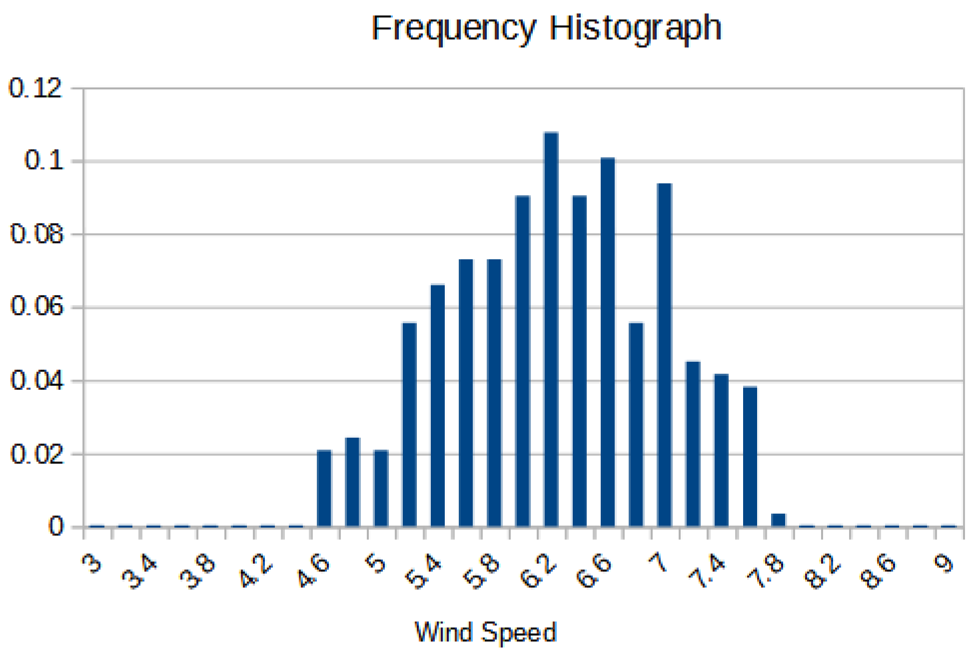


Figure 2.5 Frequency Histograph

The best fitting weibull distribution has the values of 3 as shape factor and 6.86 as scale factor.

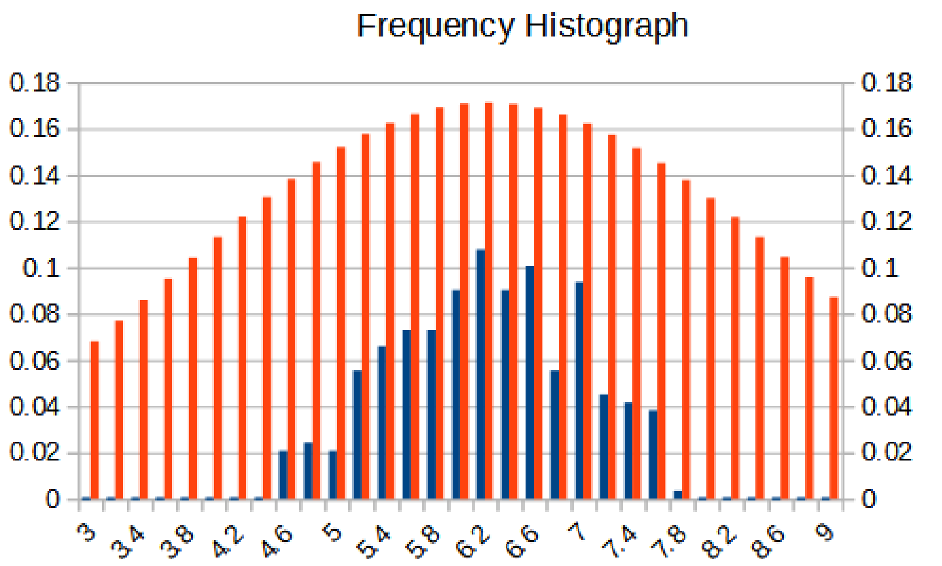


Figure 2.6 Wind Speed Frequency Histograph with Weibull Distribution

The Weibull distribution method is given to show the wind speed data more accurately. Due to the limited data available, we found the weibull parameters closest to our data by using the average wind speed to more accurately estimate the wind speed distribution.

2.2 Wind Turbines

A wind turbine is a device that converts the kinetic energy of the wind into electrical energy. They are an increasingly important source of renewable energy and are used in many countries to reduce energy costs and reduce reliance on fossil fuels. Wind turbines are produced in a wide variety of sizes with horizontal or vertical axis.

2.2.1 Hawt

HAWTs are common wind machine designs in use today. HAWTs use aerodynamic blades (i.e. blades) attached to a rotor that can be positioned upwind. HAWTs typically have two or three blades and operate at high blade tip speeds. For maximum efficiency, the axis of rotation should be parallel to the wind flow, so they are not preferred in areas where there is no dominant wind direction.

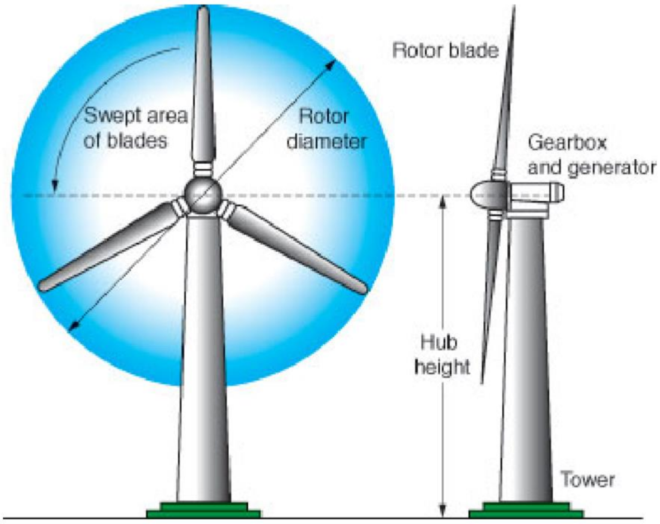


Figure 2.7 Horizontal Axis Wind Turbine [1]

2.2.2 Vawts

A vertical axis wind turbine (VAWT) is a type of wind turbine whose axis of rotation operates perpendicular to the wind direction. This allows the generator and gearbox to be placed close to the ground, facilitating service and repair. VAWTs do not need to be pointed into the wind, eliminating the need for wind sensing and steering mechanisms. The two primary types of VAWTs are:

1. Savonius
2. Darrieus

2.2.2.1 Savonius

The Savonius turbine is one of the simplest turbines. Savonius wind turbines are used to convert wind force into torque on a rotating shaft. Aerodynamically, it is a drag type device consisting of two or three buckets. When viewed from above the rotor, a machine with two buckets may resemble the letter "S" in cross section. Because of the curvature, buckets experience less drag when moving upwind than when moving upwind. Differential friction causes the Savonius turbine to rotate. Because they are drag-type devices, Savonius turbines receive much less wind power than lift-type turbines of similar size. Savonius wind turbines can operate at low wind speeds. Spontaneously The ability to start the first movement is much higher than other VAWTs.

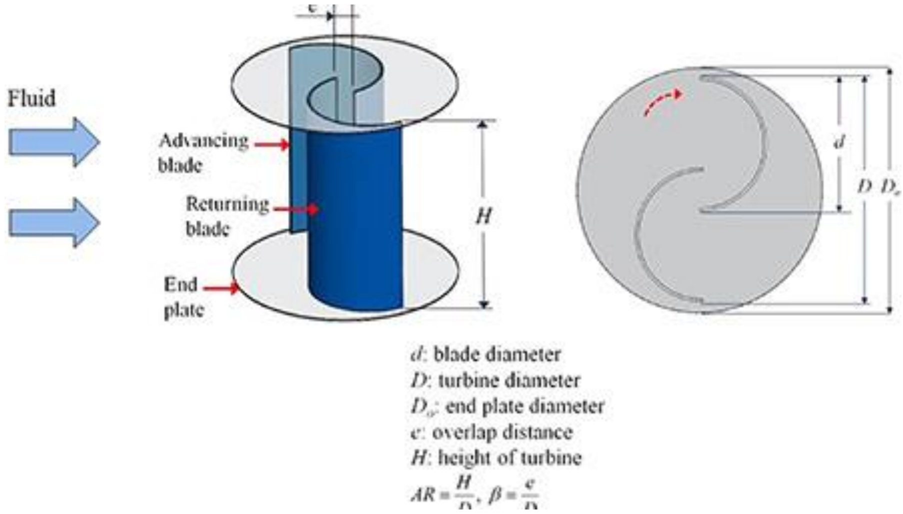


Figure 2.8 Savonius Turbine [2]

2.2.2.2 Darrieus

The turbine consists of a number of curved aerofoil blades mounted on a rotating shaft. The curvature of the blades allows the blade to be stressed only in tension at high rotating speeds. Different from Savonius turbines, Darrieus turbines have a better efficiency for high rotational speed, but lower starting torque. For this reason there are some hybrid Savonius–Darrieus turbines that try to join the positive aspects of both models. There are also several types of Darrieus type wind turbines. H-type darrieus and helical wind turbines are the most commonly used. Helical type wind turbines, keep the torque more balanced than H type Darrieus turbines but producing H type Darrieus turbines is much more eaiser and cheaper.

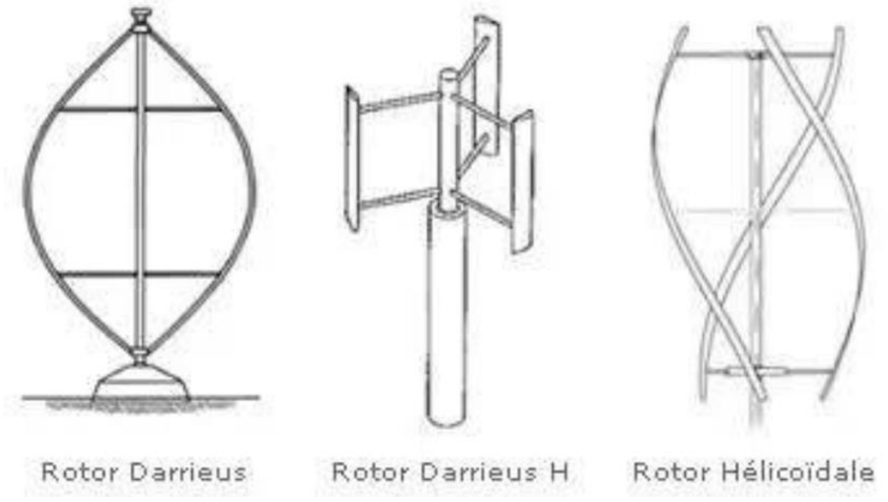


Figure 2.9 Different types of VAWTs [3]

2.2.3 Comparison of VAWTs and HAWTs

Versatile VAWTs do not need to follow the wind. This means they don't need a complex mechanism and motors to yaw the rotor and tilt the blades.

Gearbox replacement and maintenance is simpler and more efficient because the transmission is accessible from ground level instead of the operator working hundreds of feet in the air. Engine and gearbox failures are often important operating and maintenance considerations.

VAWTs can operate in conditions unsuitable for HAWTs. For example, the Savonius rotor, which can operate in erratic, slow wind ground-level contexts, is often used in remote or unattended locations, although it is the most 'inefficient', drag type VAWT.

However;

VAWTs often suffer from dynamic stalling of the blades as the angle of attack changes rapidly.

The wings of a VAWT are prone to fatigue due to the wide variation in forces applied during each turn. Vertically oriented blades bend with each turn, shortening their lifetime.

Every type of wind turbines have advantages and the difference on every design parameters effect the performance specification of the wind turbines. According to the comparison done above, it is decided to use vertical axis wind turbine in this project for the speficied study area. This section presents the theoritical background of metholodolgy of designing VAWT.

2.3 VAWT aerodynamics

Blades are very important for wind turbines. To design an efficient wind turbine, optimum blade profile and dimensions must be determined. For this, blade movements need to be understood and analyzed in terms of aerodynamics.

2.3.1 Aerodynamic airfoil and blades

An airfoil is identified using its aerodynamic parameters as shown in Figure 2.. Airfoil chord line is the the straight line connecting the leading and trailing edges and the distance from the leading edge to the trailing edge measured along the chord line is known as the aerodynamic airfoil's chord. The angle of attack (α) is defined as the angle between the relative wind (U) and the chord.

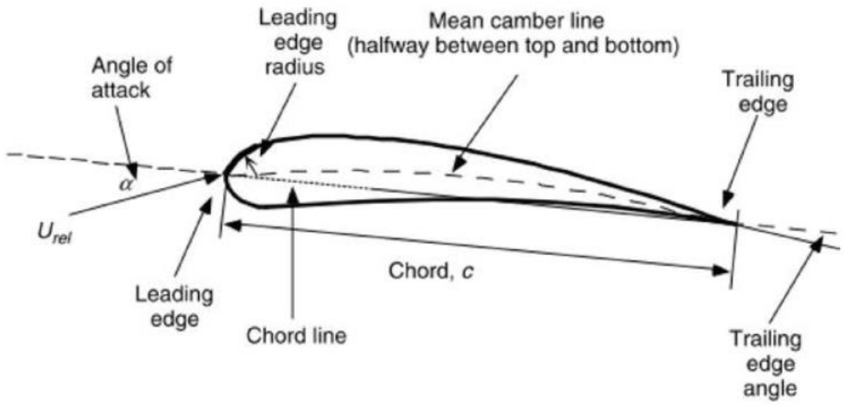


Figure 2.10 Aerofoil Seciton [4]

2.3.2 Forces acting on blades

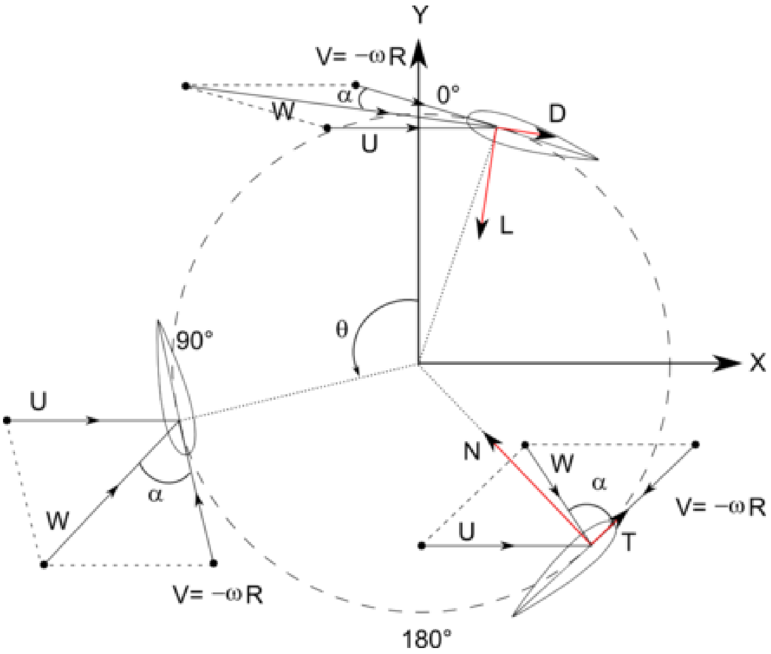


Figure 2.11 Forces Acting on Blades

Wind speed and its components acting on the blade in a steady wind flow are shown in Figure 2.12. The relative velocity vector (W) is divided into two components which are upstream air velocity(U), and tangential velocity vector of the blade(V).

$$\vec{W} = \vec{U} + \vec{V}$$

The angle (θ) is an angle value due to blade's position. Thus the oncoming fluid velocity varies during each cycle. The tangential velocity reaches maximum at θ=0° and it is minimum at θ=180°.

$$U_t = V + Ucos\theta = R\omega + Ucos\theta$$

$$U_n = Usin\theta$$

$$W^2 = Un^2 + U_t^2$$

Normal velocity(U_n), tangential velocity(U_t), rotor radius(R), angular velocity(ω)

The angle of attack (α) is related to normal velocity and tangential velocity

$$\alpha = tan^{-1}\left(\frac{Un}{U_t}\right)$$

$$\alpha = tan^{-1}\left(\frac{Usin\ \theta}{R\omega + Ucos\ \theta}\right) = tan^{-1}\left(\frac{sin\theta}{\frac{R\omega}{U} + cos\ \theta}\right)$$

Pressure distribution occurs around the profile depending on the shape of the airfoil and the angle of attack. this distribution is not uniform, One side of the blade is a low pressure region while the other side is a high pressure region, . Due to this pressure difference, forces acting on the blade occur. These forces are lifting force (F_l) and drag force (F_d). The lifting force goes in the perpendicular direction to the relative velocity. Drag force is the tangential component and occurs due to friction forces on the surface of the airfoil. The resultant of these forces could be also divided into two force components as tangential force and normal force.

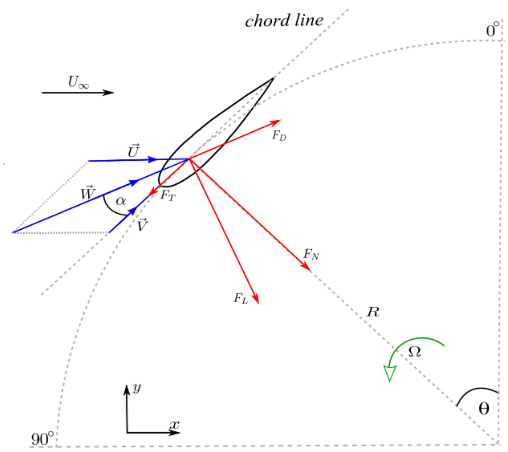


Figure 2.12 Free Body Diagram of a Blade [5]

Numerical simulation of a vertical axis wind turbine airfoil experiencing dynamic stall at high Reynolds numbers Brian Handa , Ger Kellya , Andrew Cashmana,∗

All these forces are related to air density(ρ), the blade area(A_b) which is multiplication of chord lenght and blade height, the relative velocity(W) and the special coefficitiens for each forces.

$$Fd = \frac{1}{2} \cdot \rho \cdot C_d \cdot A_b \cdot W^2$$

$$Fl = \frac{1}{2} \cdot \rho \cdot Cl \cdot A_b \cdot W^2$$

$$Ft = \frac{1}{2} \cdot \rho \cdot C_t \cdot A_b . W^2$$

$$Fn = \frac{1}{2} \cdot \rho \cdot C_n \cdot A_b . W^2$$

The tangential and normal coefficients are depend on angle of attack(α) and can be written in terms of lift and drag coefficients.

$$C_t = Cl \cdot sin\ \alpha - Cd \cdot cos\ \alpha$$
$$C_n = Cl \cdot cos\ \alpha + Cd \cdot sin\ \alpha$$

2.3.3 Tip-speed ratio (λ)

Tip-speed ratio (TSR) is the ratio between the tangential speed of the tip of a blade and the actual speed of the wind. The tip-speed ratio is related to efficiency, with the optimum varying with blade design.Higher tip speeds result in higher noise levels and require stronger blades due to larger centrifugal forces.

$$\lambda = \frac{tip\ speed\ of\ blade}{wind\ speed} = \frac{R \cdot \omega}{U} = \frac{2 \cdot \pi \cdot n \cdot R}{60 \cdot U}$$

Here, ω is the angular velocity [rad/s], R is the rotor radius, n is the revolution, and U is the wind speed.

Tip speed ratio is used as a parameter in (Cp) power coefficient curves.

2.3.4 The power coefficient

The power coefficient, is a quantity that expresses what fraction of the power in the wind is being extracted by the wind turbine. It is generally assumed to be a function of both tip-speed ratio and pitch angle.

The amount of power that can be absorbed by the turbine is,

$$P = \frac{1}{2} C_p \rho A_s U^3$$

A_s is the swept area of the turbine which equals to multiplication of the rotor radius and blade lenght. The C_p is the power coefficient. This coefficient represents the energy produced by the turbine as part of the total wind energy that passes through the swept area.

$$C_p = \frac{P}{P_{wind}} = \frac{P}{\frac{1}{2}\rho U^3 A_s}$$

According to the Betz Limit, a wind turbine can only convert 59% of the kinetic energy of the wind into mechanical energy under ideal conditions. In real wind turbines, mechanical and electrical losses occur outside of these ideal situations, and after these losses are calculated, the power and efficiency of the wind turbine can be determined.

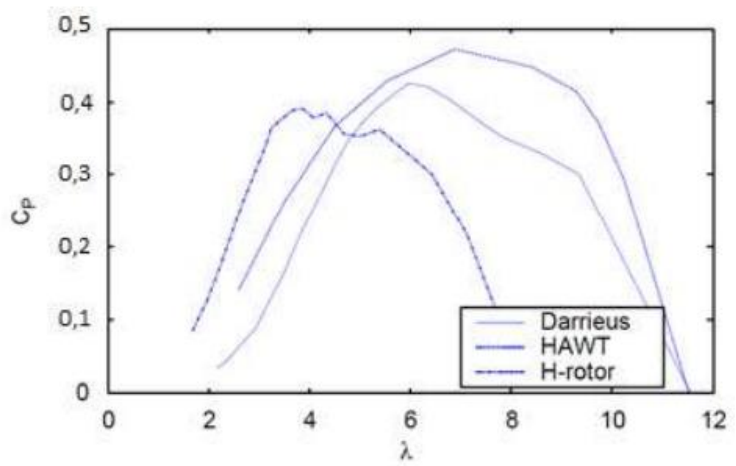


Figure 2.13 Cp-TSR curves for Different Turbine Types [6]

This is a graph of different types of wind turbines comparing the variation of the power coefficient with the changes in the tip speed ratio when the pitch is held constant.

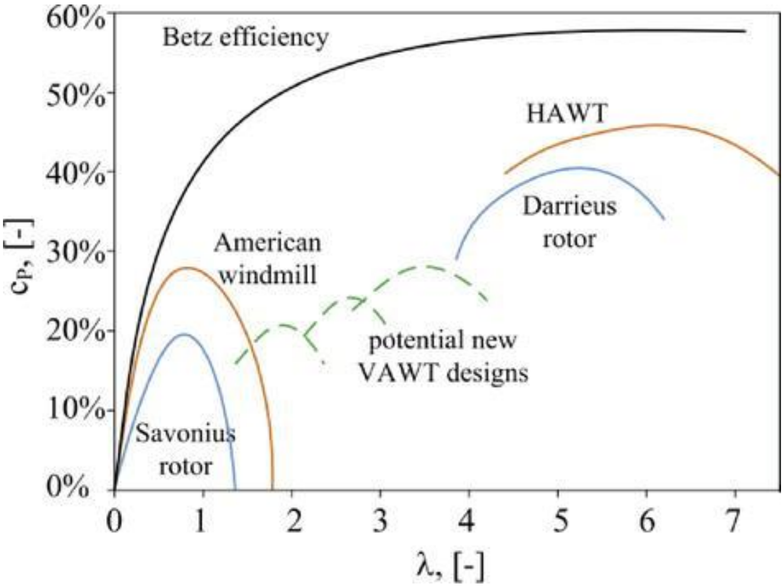


Figure 2.14 Cp-TSR curves for Different Turbine Types [7]

This is another graph shows the relation between power coefficient and tip speed ratio. According to both graphs, the range of tip speed values of (λ=3;λ=6) is a good range to refer to these tip speed ratio values to achive higher power coefficient.

2.3.5 Reynolds Number

Reynolds number defines the characteristics of flow conditions. Power coefficient curves vary according to the Reynold number.

$$\Re = \frac{c.U.\lambda}{v_k}$$

Where, U is the velocity of the wind, λ is the tip speed ratio and $v_k$is the air's kinematic viscosity.

The Reynolds number strongly influences the power coefficient of a vertical-axis wind turbine. Furthermore, it changes as the main dimensions of the turbine rotor change. Increasing rotor diameter rises the Reynolds number of the blade.

2.3.6 Solidty

The solidity of the turbine (σ), is defined as the developed surface area of all blades divided by the swept area . Solidty has a strong influence on VAWT performance.

$$\sigma = \frac{Nc}{R}$$

Total blade area is less with lower solidty value. This makes the blade ligther. This benefits wind turbine performance as higher rotation speeds can be achieved.

VAWTs with high solidty values reach optimum efficiency at low TSR but this efficiency ends quickly on either sides of this optimum.

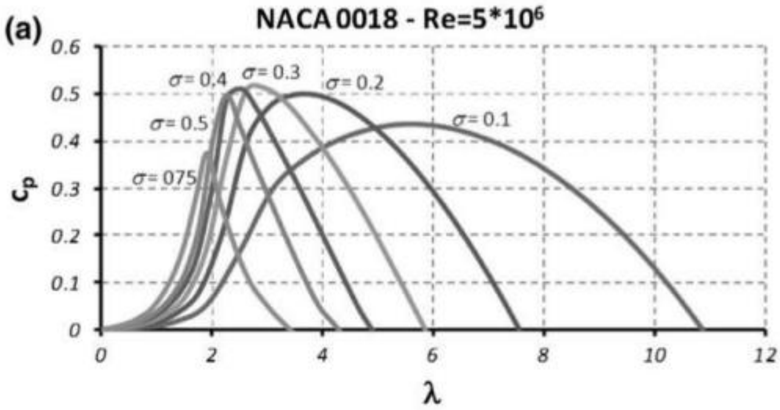


Figure 2.15 Effect of Solidty on Cp-TSR Curves [8]

This Figure 2.17 shows the effects of solidty number to power curves in constant Reynold Number. As it seen in the Figure 2.17, the higher solidty value reaches the peak power coefficient value in lower TSR and it drops away as fast as it reaches the peak.

2.3.7 Cross-sectional area of the turbine and aspect raito (R/H):

The cross-sectional area of wind turbines has a direct effect on the output power value. In vertical wind turbines, the cross-sectional area is rectangular and is obtained by multiplying the rotor radius and the blade height.

The turbine's aspect ratio (AR) as the ratio between blade height and rotor radius (AR = h/R).

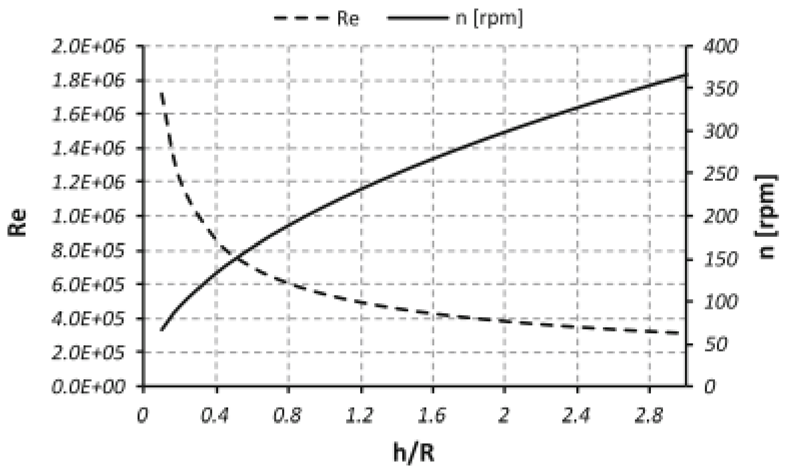


Figure 2.16 Reynolds Number and Revolution speed - Aspect Ratio Curves [8]

According to the diagram above, the aspect ratio directly affects the number of revolutions. With lower aspect ratios, turbines rotate slower but with higher torque. The decrement in aspect ratio also increases the Reynold Number which is important for Power coefficient- TSR curves.

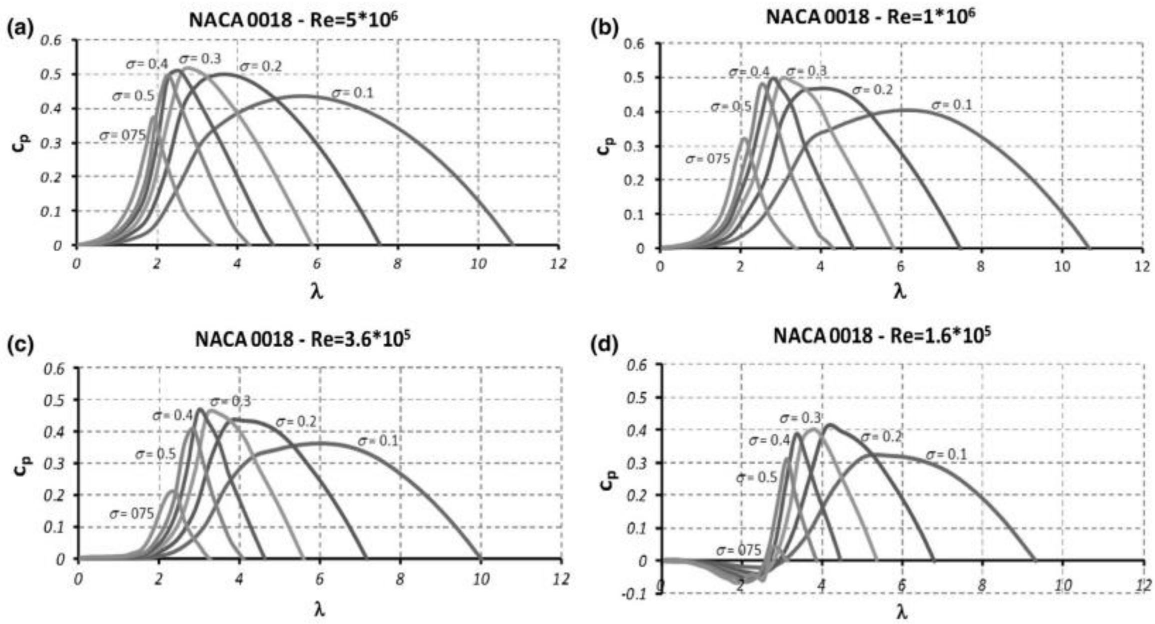


Figure 2.17 Effect of Solidty on Cp-TSR Curves for Varying Reynolds numbers [8]

These figures shows the power coefficient curves for the wind turbine with the NACA 0018 airfoil, at different Reynolds numbers. As it seen, The power coefficients are higher with higher Reynold numbers.

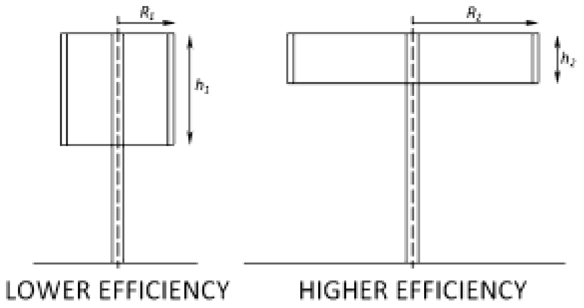


Figure 2.18 Aspect Ratio's Effect on Efficiency [8]

So, to maximize the power coefficient, the rotor's aspect ratio should be as small as possible. with the lower aspect ratio, it will become easier for wind turbine to self start which is typical problem for VAWTs.

The biggest disadvantage of lower aspect ratio is that it works in slower windfields. With lower aspect ratio, the turbine can rotate easily but this limits the revolution per minute which is not good for normal or faster windfields. So in order to make an efficient wind turbine, the optimum aspect ratio should be selected.

2.3.8 Airfoil Geommetry and Airfoil Chords:

Airfoil design and chord lenghts are very important design parameters for higher performance of wind turbines. The chord length is the distance between the trailing edge and the point where the chord intersects the leading edge.

There are several airfoils like DU of Delft University of Technology, SERI of the US National Renewable Energy Laboratory, FFA-W of the Swedish Aeronautical Research Foundation, Althaus and FX developed by Wortmann, Danish Riso National Laboratory of RISO and the US National Aeronautics and Advisory Committee of NACA. The most widely used airfoil among these is NACA airfoils.

NACA airfoils are expresed with multi digit numbers (i.e NACA XXXX). Each number represents special parameter in blade profile. The first number as a percentage maximum hump ratio, the second number is ten times from the leading edge of the maximum hump in percent from position; third and The fourth number is the maximum thickness ratio as a percentage. shows.

The airfoil types NACA 00XX are symmetrical and most common in Darrieus type wind turbines.

Self-start rotating of Darrieus type wind turbines is harder than Savonius type . Thickening the blade provides the initiation effect. It may be necessary to establish a mechanism that will give the initial rotation speed to the wind turbines with a thin blade profile.

Thin airfoils are able to rotate at higher speeds Therefore, the NACA 0012 and NACA 0015 profiles can be used. However, in terms of durability Airfoil type NACA0018 is the most widely used.

2.3.9 Number of blades

Number of blade effects the solidty value directly. Each design is unique for each application and requires specific design parameters so it’s important to analyze the relationship between the geometric parameters of the turbine.

VAWTs have generally two or three blades because for a constant solidty value, having a fewer blade with larger chord is better than more blades with a smaller chord because bending stresses are depend on the square of the chord size but the aerodynamics loads are dependet on only the first power of the chord.

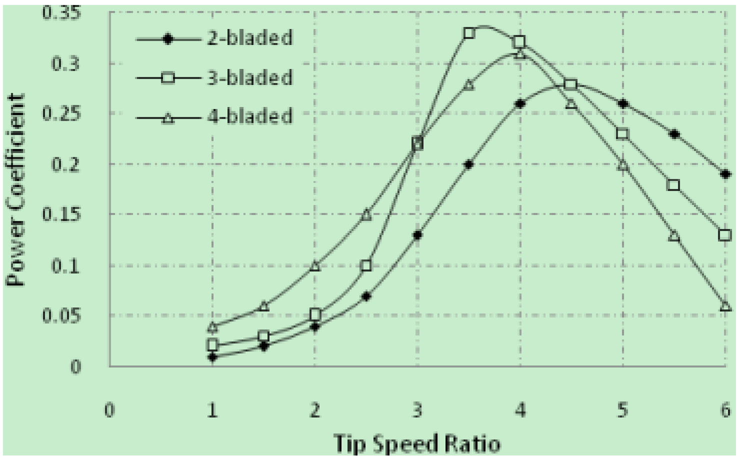


Figure 2.19 Effect of Number of Blades on Cp-TSR curves [9]

This Figure 2.20 shows Power coefficient variations of H- Darrieus wind turbines based on number of blades. As it seen, the 3-bladed H-Darrieus perform more efficient than 2 and 4 bladed turbines.

2.4 Design Procedure

This section presents the considerations and parameters necessary for the construction of VAWTs. Since there are many different variables, it is quite difficult and complex to design a wind turbine. For this reason, some assumptions and reference values should be taken when starting the design.

2.4.1 Material selection

Turbine blades must be light, resistant to weather variations and fatigue. Because it light, cheap and easy to shape, XPS foam cut in the shape of the airfoil would be good choice. It is decided to cover the blade with E-glass fiber epoxy to make the blades stregnthful and durable. The blades will be connected to the struts which is a support between the shaft and the blades, with aluminum rods passing through the foam in order to make it more stable and help protecting blades from bending. The mechanical properties of glass fiber epoxy is shown in table below [10].

Amount of Glass Fiber (%)	65
Density (kg/m^3)	2000
Yield Strength(MPa)	1000
Flexual Strength (MPa)	1400

Table 2.2 Mechanical Properties of Glass Fiber Epoxy

AISI 1020 steel provides the optimal machinability properties and is typically used in many industrial rotational engineering applications, such as shafts, for its mechanical properties. AISI 1020 cold drawn steel will be used as material of shaft,stuts and the tower.

Density	7900 kg/m^3
Tensile Strength	420 MPa
Yield Strength	350 MPa

Modulus of Elasticity	186 Gpa
Shear Modulus	72 GPa
Poisson's Ratio	0.29

Table 2.3 Mechanical Properties of AISI 1020 CD Steel

2.4.2 Desired power

Power of the wind turbine is expressed as,

$$P = \frac{1}{2} \cdot \rho \cdot U^3 \cdot 2R.H.C_p$$

Where, ρ is the density of air, U is the wind velocity, R is the rotor radius, H is the height of the blade and C_p is the power coefficient of the wind turbine. The geometrical aspects depends on the desired power and the velocity of air so firstly the desired power of the wind turbine should be determined.

In this project, VAWT will be designed with the capacity of 1KW for mean wind speed of 6.13 m/s. The density of air $p = 1{,}225k\ g/m^3$ and kinematic viscosity of air is $v = 1{,}647.10^{-5}$and the power coefficient is assumed as $C_p = 0{,}53$.

2.4.3 Geometrical parameters

The aspect ratio (H/R) is decided as 1.5 in order to increase the reynolds number and the efficiency of the turbine. This will also helps to the turbine for self start rotating, which is typical problem for H type VAWTs.

$$1000W = \frac{1}{2} \cdot 1{,}225\ kg/m^3 \cdot 6{,}13^3\ m/s \cdot 2R.H.0{,}53$$

$$6.69 = R.H, 1.5 = H/R$$

By solving these equations, we get R=2.1m and H=3.1m. (Both rotor radius and blade height is rounded to nearest decimal in order to make the production eaiser and the effect of it is negligible.)

Number of blades are 3 and the airfoil is selected as NACA 0018 in order to help the turbine on self start rotating and to increase the durability of blades while making the turbine efficient.

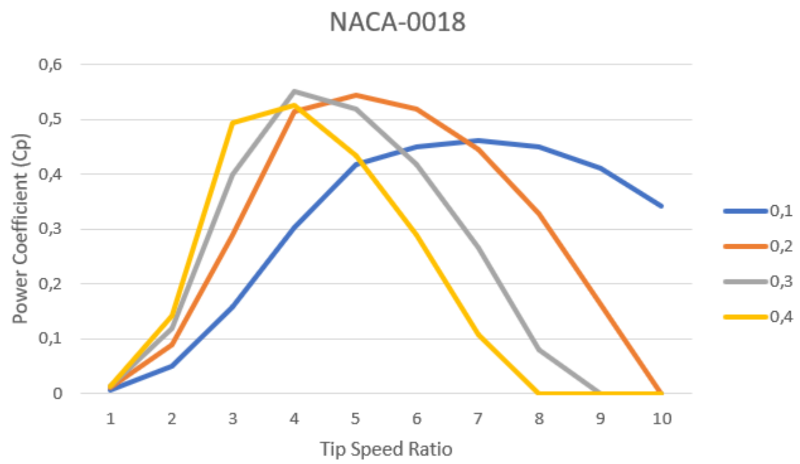


Figure 2.20 Cp-TSR Curves for Different Solidty Values

This Figure 2.22 shows the effect of the solidty to the power coefficient curves. This graph of an analysis made by Qblade program for the parameters stated above. As it seen from the graph, most efficient solidty value is σ=0.3 and the highest power coefficient value is Cp=0.55 at TSR=4. (The power coefficient is very close to assumpted power coefficient above so there is no need for another iteretion.)

The chord length will be,

$$\sigma = \frac{Nc}{R} = 0{,}3 = \frac{3c}{2.1} \rightarrow c = 0.21m$$

The number of revolutions becomes,

$$\lambda.V = \frac{2.\pi.R.N}{60} \rightarrow 4 \times 6{,}13 = \frac{2.\pi.2{,}1.N}{60} \rightarrow N = 111.5rpm$$

The air friction or other mechanical losses are not included to this equation so the true number of revolution will be less then the found one.

Reynolds number,

$$\Re = \frac{c.V.\lambda}{\nu} = \frac{0{,}21 \times 6{,}13 \times 4}{1{,}647 \times 10^{-5}} = 3{,}13 \times 10^{5}$$

Torque becomes,

$$T{\times}\omega{=}P$$

$$\left(\frac{1000W}{111.5rpm} \times \frac{60}{2 \times \pi}\right) = 85.6N.m$$

So the design parameters so far,

Parameters	Design
Power (kW)	1
Airfoil	NACA-0018
Wind Speed(m/s)	6.13
Air Density(kg/m^3)	1.225
Kinematic viscosity(m^2/s)	1.647x10^{-5}
Number of Blades	3
Max. Power Coefficient	0.55
Solidty	0.3
TSR_{Cpmax}	4
Rotor Radius(m)	2.1
Blade Heigth(m)	3.1
Chord length(m)	0.21

Revolution(rpm)	111.5
Reynolds Number	3,13x10^5
Torque(N.m)	85.6

Table 2.4 Design Parameters

In order to design the structural components, some parameters needed to be known such as the radial forces, weigths etc. These parameters are obtained with the computational analyzes.

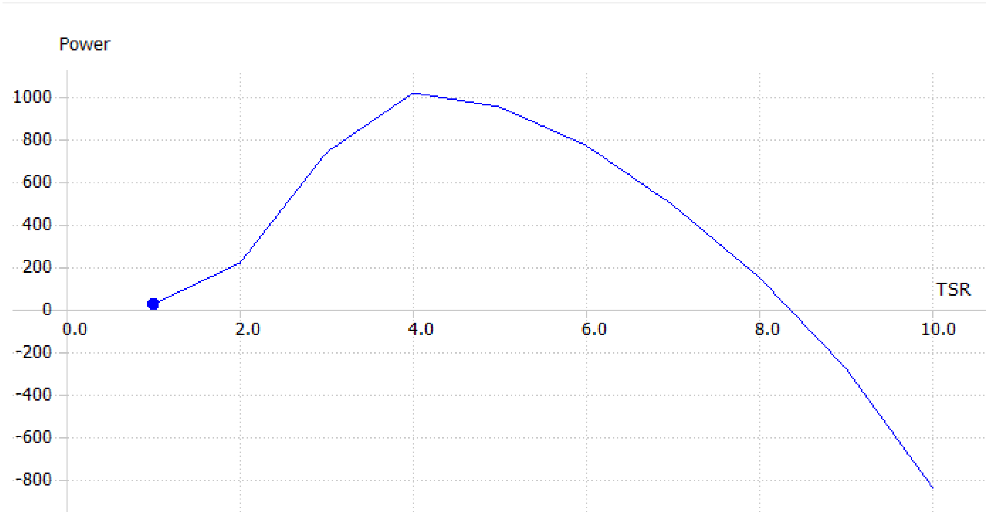


Figure 2.21 Power-TSR Curve

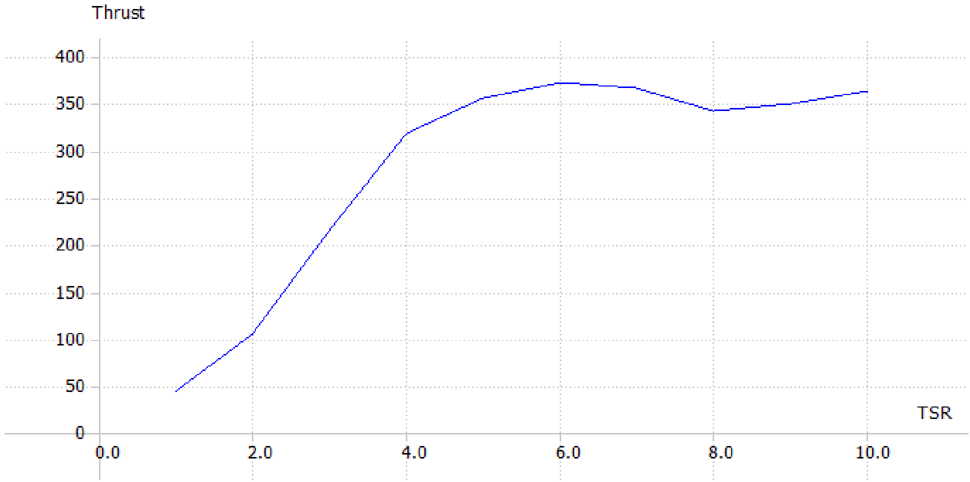


Figure 2.22 Thrust - TSR curve

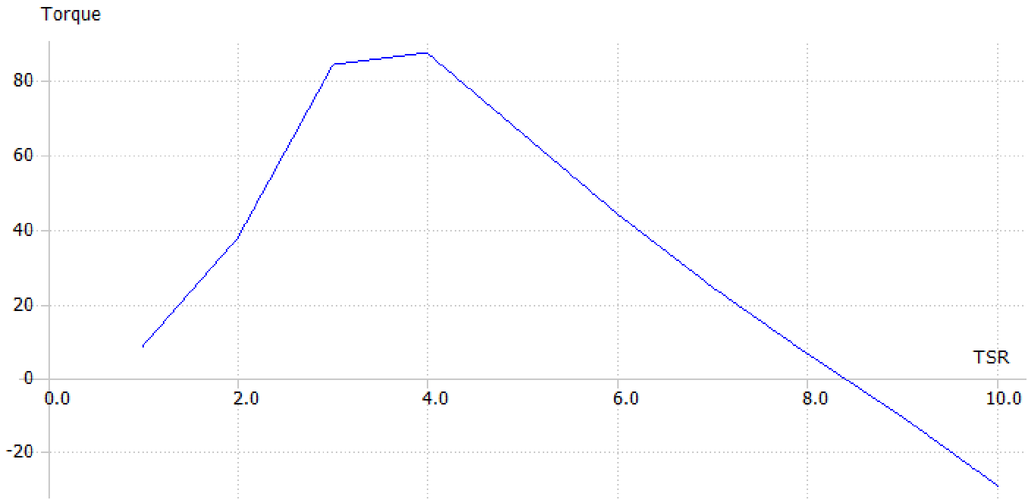


Figure 2.23 Torque - TSR Curve

This 3 figures are simulations results obtained by the Q-blade program. The power output and the torque are equal to the values obtained theoritically. These outputs could be considered as refference values for structural design but this would result higher error ratios. The main reason of this is that these output valid for steady state conditions. In real life, the forces acting on the blades could be higher because of a phanomenon called dynamic stalling and low friction forces before the turbine becomes steady state.

Dynamic stalling reduction in the lift coefficient generated by a foil as angle of attack increases. This occurs when the critical angle of attack of the foil is exceeded. The critical angle of attack is typically about 15°, but it may vary significantly depending on the fluid, foil, and Reynolds number [11].

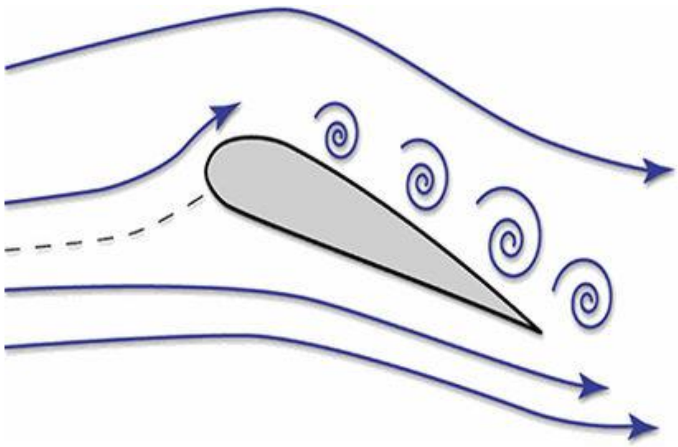


Figure 2.24 Dynamic Stall [12]

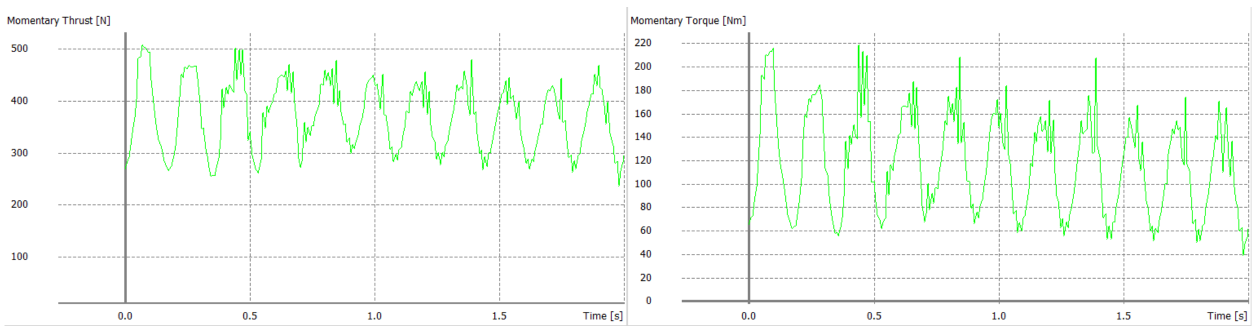


Figure 2.25 Momentary Thrust and Momentary Torque Curves

These figures shows the momentary thrust and torque. As it seen the peaks of both parameters are occured at the beginning of the simulation, where the friction caused by the wind is less. So the total radial force acting on blades will be considered as 500N in order to make the design safer.

Kütle = 15916.13 gram

Hacim = 119928703.31 milimetre küp

Yüzey alanı = 18750656.14 milimetrekare

Figure 2.26 Physical Properties of blades

Some mechanical parameters of 3 blades including E-glass fiber cover and aluminum mills.

2.5 Structural design

While working on maximum efficiency, a VAWT must be able to withstand all the forces and wind loads. The Structural design of VAWTs contains couple of components, which are subjected to different loads and these components should be designed within some criterias individually. These components are shown in the Figure 2.27.

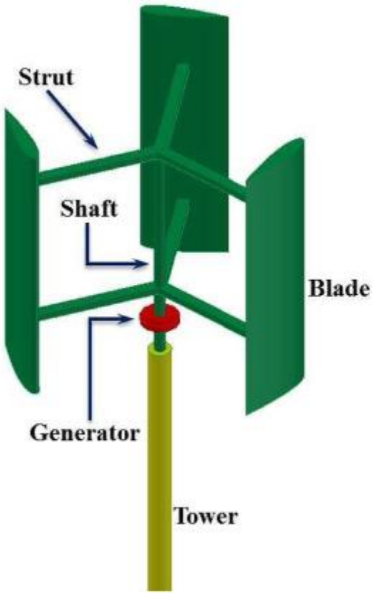


Figure 2.27 Structural components of a VAWT [13]

In order to design the structural components, some parameters needed to be known such as the radial forces, weigths etc. These parameters are obtained with the computational analyzes.

2.5.1 Struts

The struts are the structural components connecting the VAWT blades to the support column, hub or to the shaft. The configuration of the strut system was determined by the blade design analysis. The blade could be modeled as a simply supported beam, where the support locations represent where the struts are attached.

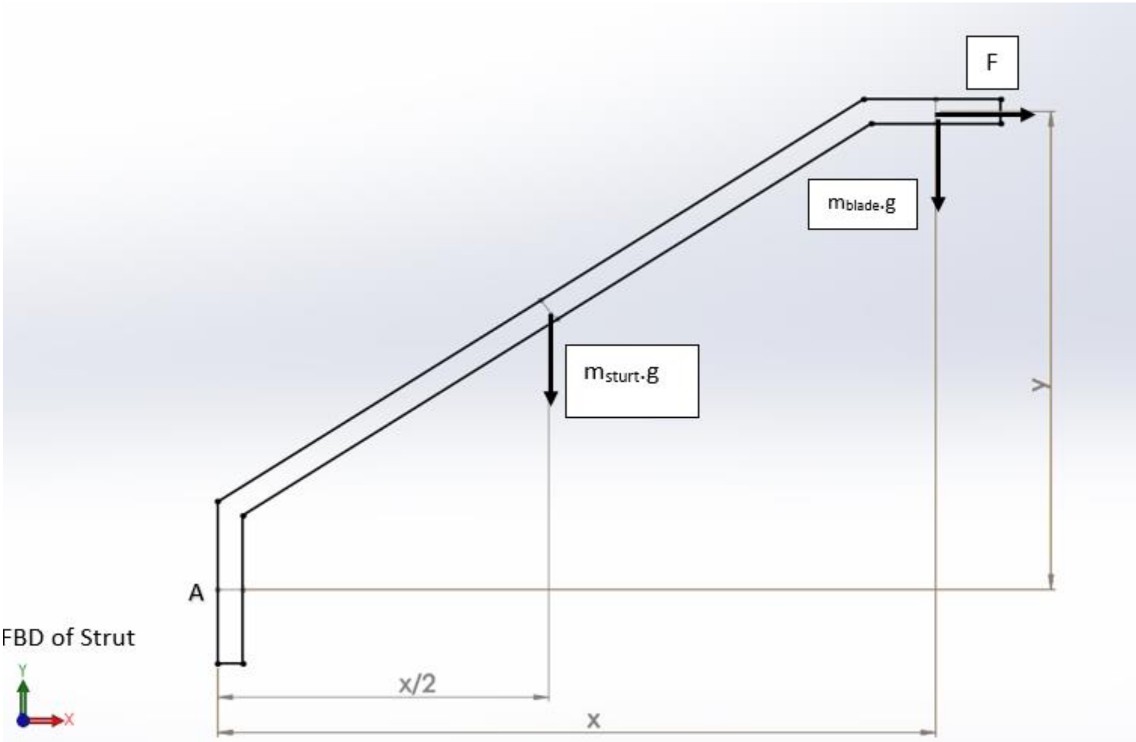


Figure 2.28 Forces Acting on Sturt

Struts are subjected to the weigth of itself, weigth of the blades and the thrust force which is the summation of all the radial forces acting on the blades. Struts should be able to carry all these loads while withstanding the created momentum so strut placing is very important as a design parameter. Increasing the heigth will help to make the hub smaller but it requires bigger struts which make the rotor heavier. With the lower heigth, strut can stand aganist all the loads but this time, the forces acting on the hub by the struts will become much larger and this requires much more central hub and shaft. The dimensions parameters are obtained by several testing in order to find the optimum dimensions. The cross-sectional area of the sturt is considered as square and the safety factor is 3.

The Moment at point A will be,

$$M = \left(\frac{m_{blade}}{2}\right)(g)(x) + (m_{strut})(g)\left(\frac{x}{2}\right) + \left(\frac{F}{2}\right)(y)$$

$$M = \left(\frac{5.3kg}{2}\right)(9.81)(2{,}1m) + \left(A_{strut} \times 2.26m \times 7900\,\frac{kg}{m^3}\right)(9{,}81)\left(\frac{2{,}1m}{2}\right) + \left(\frac{500N}{2}\right)(1m)$$

$$M = (54.6 + 183905 \times a^2 + 250)Nm$$

The bending stress:

$$\sigma = \frac{M \times \frac{a}{2}}{\frac{a^4}{12}} \leq \frac{S_y}{n}$$

$$\frac{(304.6 + 183905 \times a^2) \times 6}{a^3} \leq \frac{350 \times 10^6}{3} Pa \rightarrow d = 28.5mm \cong 30mm$$

Kütle = 116210.86 gram

Hacim = 132672632.96 milimetre küp

Yüzey alanı = 20464641.39 milimetrekare

Figure 2.29 Physical Properties of Blades and Strut

2.5.2 Shaft

Shaft rotates with the blades simultaneously and transmits this rotation to the generator directly in order to produce power. Shaft is connected to blades with struts and it is subjected all the forces, the moments and all the weigth of the rotor. While transmitting, shaft should not fail due to axial loads and bucklicks. To achive that, proper shaft diameter is needed be determined.

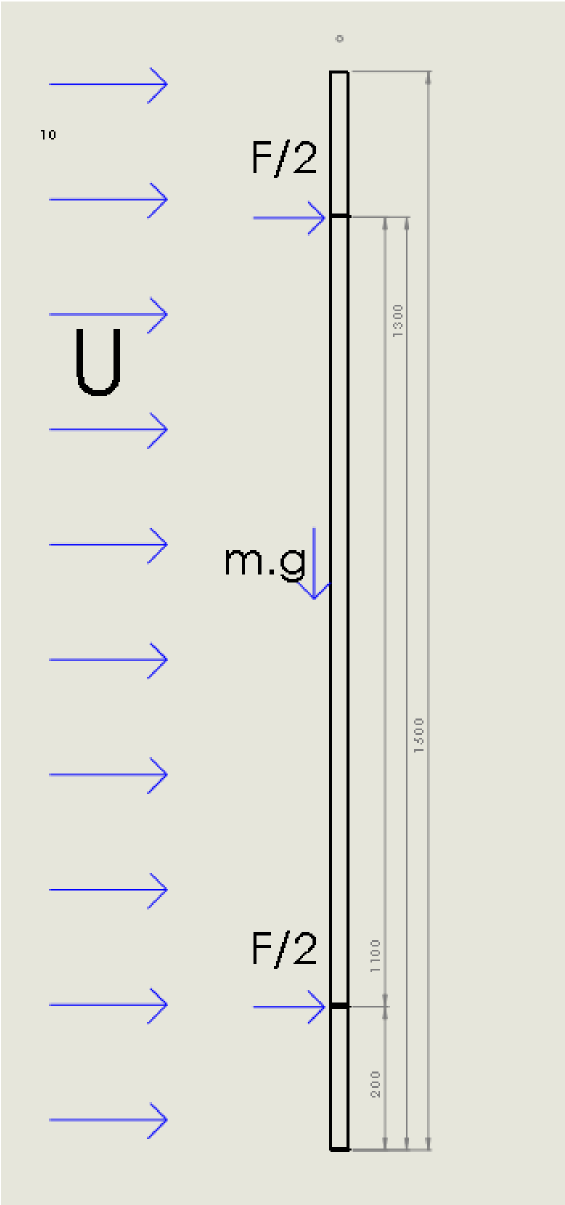


Figure 2.30 Forces Acting on Shaft

The free body diagram of shaft is shown in the Figure 2.31. Shaft also rotates so it has a torque and this should be considered as well. It has all the resultant forces in locations where each 3 struts of 6 are connected to the shaft.

$$\sigma_{bending} = \frac{32 \times M}{\pi \times d^3}$$

$$\sigma_{axial} = \frac{4 \times m \times g}{\pi \times d^2}$$

There will be distributed load on the shaft caused by the wind which increases the total momentum on the shaft,

$$F_U = \frac{1}{2} \times p \times U^2 \times C_d \times d \times L$$

Here, the drag coefficient C_d is taken as 1.1 and L is length of the shaft which is 1.8m.

$$F_U = \frac{1}{2} \times 1.225 \left(\frac{kg}{m^3}\right) \times 6.13(m/s)^2 \times 1.1 \times d \times 1.8m = d{\times}45{,}57Nm$$

$$M = \frac{500}{2} N{\times}1.3m + \frac{500}{2} N{\times}0.2m + 45.57N{\times}\frac{1.5m}{2} \times d = 375Nm + 68.34{\times}d\ Nm$$

$$\sigma_{axial} = \frac{4 \times 116.21kg \times 9.81\, m/s^2}{\pi \times d^2} = \frac{1451.51}{d^2}$$

The maximum momentary torque is 220 Nm so,

$$\tau = \frac{16 \times (220)}{\pi \times d^3}$$

$$\sigma = \sigma_{bending} + \sigma_{axial}$$

$$\frac{\sigma}{2} + \sqrt{\frac{\sigma^2}{4} + \tau^2} \leq S_y \rightarrow d = 23mm \cong 25mm$$

Kütle = 122005.62 gram

Hacim = 133408943.74 milimetre küp

Yüzey alanı = 20583432.86 milimetrekare

Figure 2.31 Physical Properties of Rotor including Shaft

2.5.3 Tower

Tower carries the whole rotor, covers and protects shaft and other components. It is subjected to wind loads, the rotor forces and the weigth of the VAWT which means the tower is under shear stresses, axial stresses and bendings. Tower is the biggest structural component so in order to reduce the cost, the thickness of the tower should be minimized while carrying all the loads. The height of the tower is 4m and it is vertical cyclinder with inside radius of 150mm.

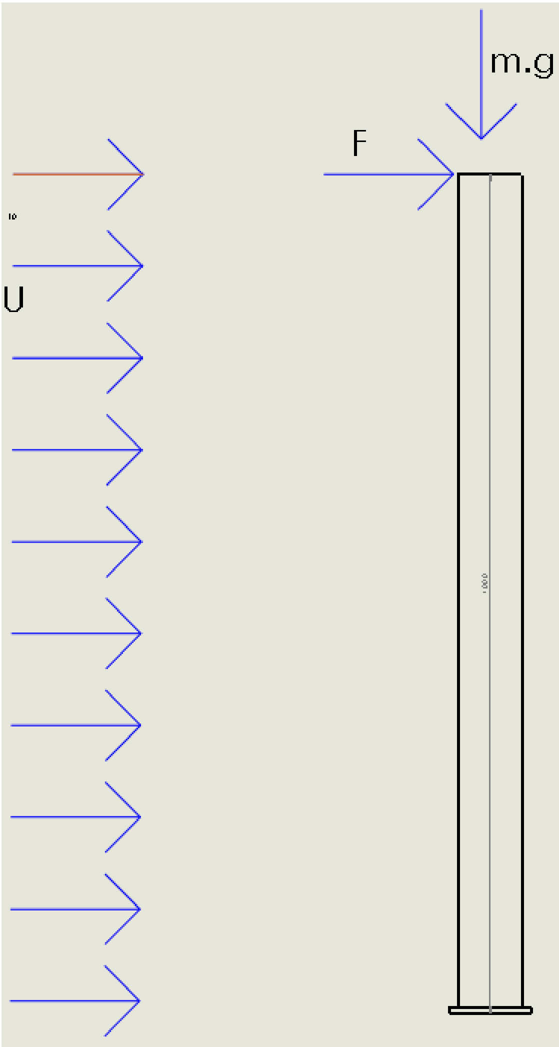


Figure 2.32 Forces Acting on Tower

$$\sigma_{axial} = \frac{4 \times m \times g}{\pi \times (r_o^2 - r_i^2)}$$

Here, $r_o \wedge r_i$ are the outside and inside radius of the tower respectively. The total weight that the tower is subjected to also contains the weigth of the tower it self so,

$$m_{tower} = \pi \times (r_o^2 - r_i^2) \times H_{tower} \times 7900\,\frac{kg}{m^3}$$

$$\sigma_{axial} = \frac{4 \times m \times g}{\pi \times (r_o^2 - r_i^2)} = \frac{4 \times (122kg + m_{tower}) \times 9.81\,\frac{m}{s^2}}{\pi \times (r_o^2 - r_i^2)}$$

$$F_U = \frac{1}{2} \times p \times U^2 \times C_d \times 2 \times r_o \times H_{tower}$$

$$F_U = \frac{1}{2} \times 1.225\left(\frac{kg}{m^3}\right) \times 6.13(m/s)^2 \times 1.1 \times 2 \times r_o \times 4m = r_o \times 202.54Nm$$

Total bendin moment on the tower,

$$\sum M_{tower} = F \times H_{tower} + F_U \times H/2$$

$$F \times H_{tower} = 500N \times 4m = 2000Nm$$

$$\sum M_{tower} = 2000Nm + r_0 \times 202.54 \times 2$$

Bending stress,

$$\sigma_{bending} = \frac{M_{tower} \times \frac{r_0}{2}}{I}$$

$$I = \frac{\pi(r_o^4 - r_i^4)}{64} = \frac{\pi(r_o^4 - 0.15^4)}{64}$$

Shear stress,

$$\sigma_{shear} = \frac{F_U \times H/2}{\pi \times (r_o^2 - r_i^2)}$$

Von mises stress,

$$\sigma_{von-mises} = \frac{(\sigma|bending + \sigma_{axial})}{2}\sqrt{\frac{(\sigma|bending + \sigma_{axial})^2}{4} + \sigma_{shear}{}^2} \leq 350MPa \to r_o = 152mm$$

The 152mm outer radius with 2mm thickness satisfies the requirements for AISI 1020 CD steel. All forces are calculated for the tower heigth of 4m. Inner diameter is selected as 150mm the tower will have generator inside and it should be large enough for maintenance purposes.

2.5.4 Generator

Generator converts the mechanical energy of the rotor to the electrical energy. Different types of generators can be used VAWTs and each one of them have their own advantages. In this design, it is decided to use permanent magnet generators. This generator can directly mounted to the rotor by the shaft so there is no need for gearbox or belt system for connection.

3. RESULTS AND DİSCUSSİON

3.1 Final design

In this section, the final VAWT design, drawing and mountations will be stated. A vertical axis wind turbine is designed with theoritical calculations and computitional simulations. In order to make the blades thin, stable and durable, xps foam with glass fiber epoxy cover is used as a blade material. The struts, shaft and tower are under too much loads so cold drawn AISI 1020 steel is selected as a material of them. This material selection will keep the turbine safe and functional even under high circumstances. The final turbine shown in the Figure 3.1.

Figure 3.1 Final Turbine Design

The struts are connected to the blades with aluminum rods inside the blades. The loads on the blades will be transfer to the struts through this rods, and goes directly to the shaft. The shaft and struts will be under heavy axial and radial loads and in order to fully transfer the rotation of blades to the shaft. As a bearing, tapered roller bearing is used to carry all the axial loads of the rotor while rotating and it is mounted to the tower with a cover. The structural assembly is shown in the Figure 3.2.

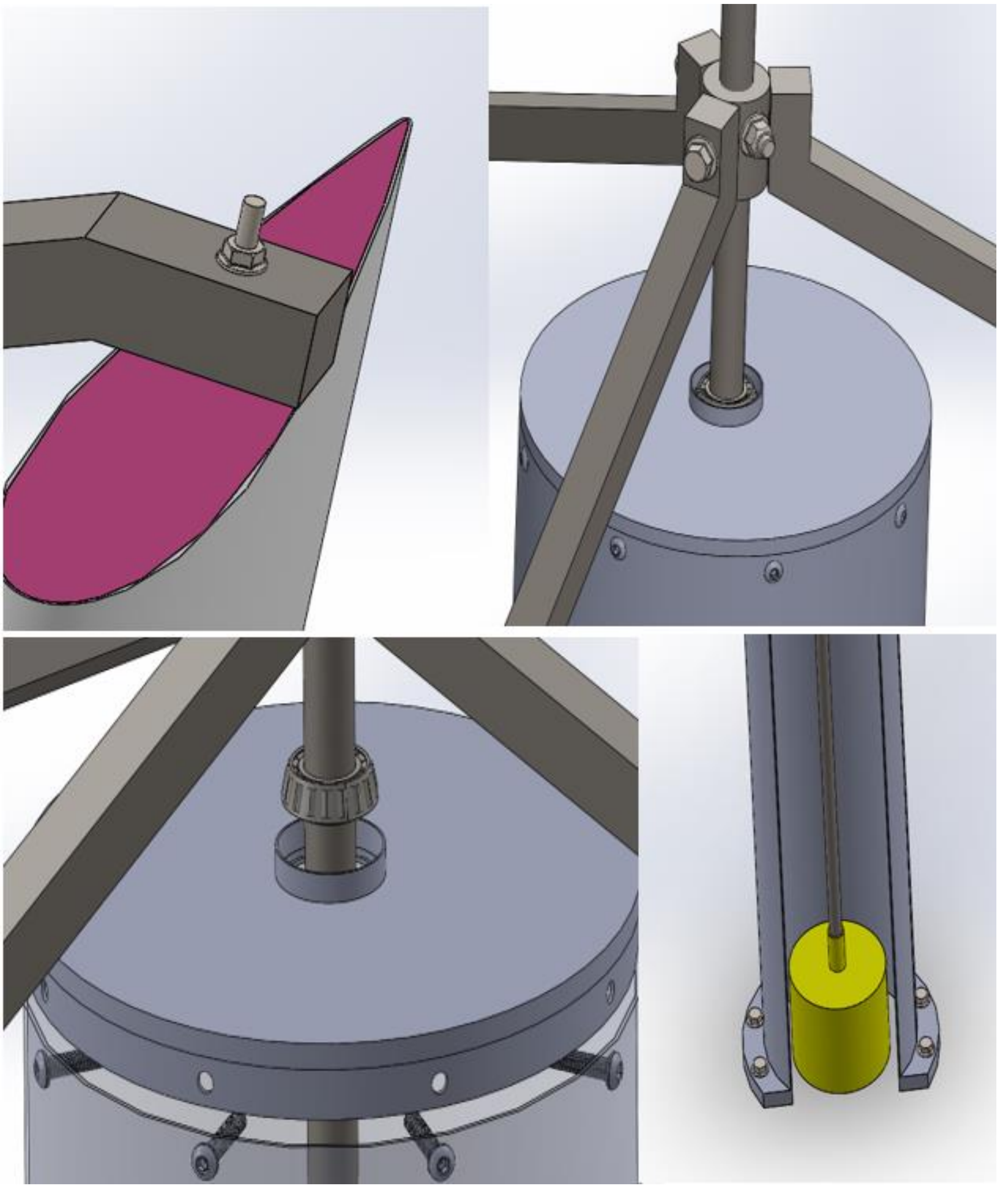


Figure 3.2 Structural Assembly

3.2 Structural analysis

3.2.1 Blades

The Figure 3.3 shows the static analysis of the blade. The maximum displacement is 6.593×10^{-3}mm and it neglibile compared to 3.1m long blade. The von-mises stress on the blade is also much less than it's yield strength.

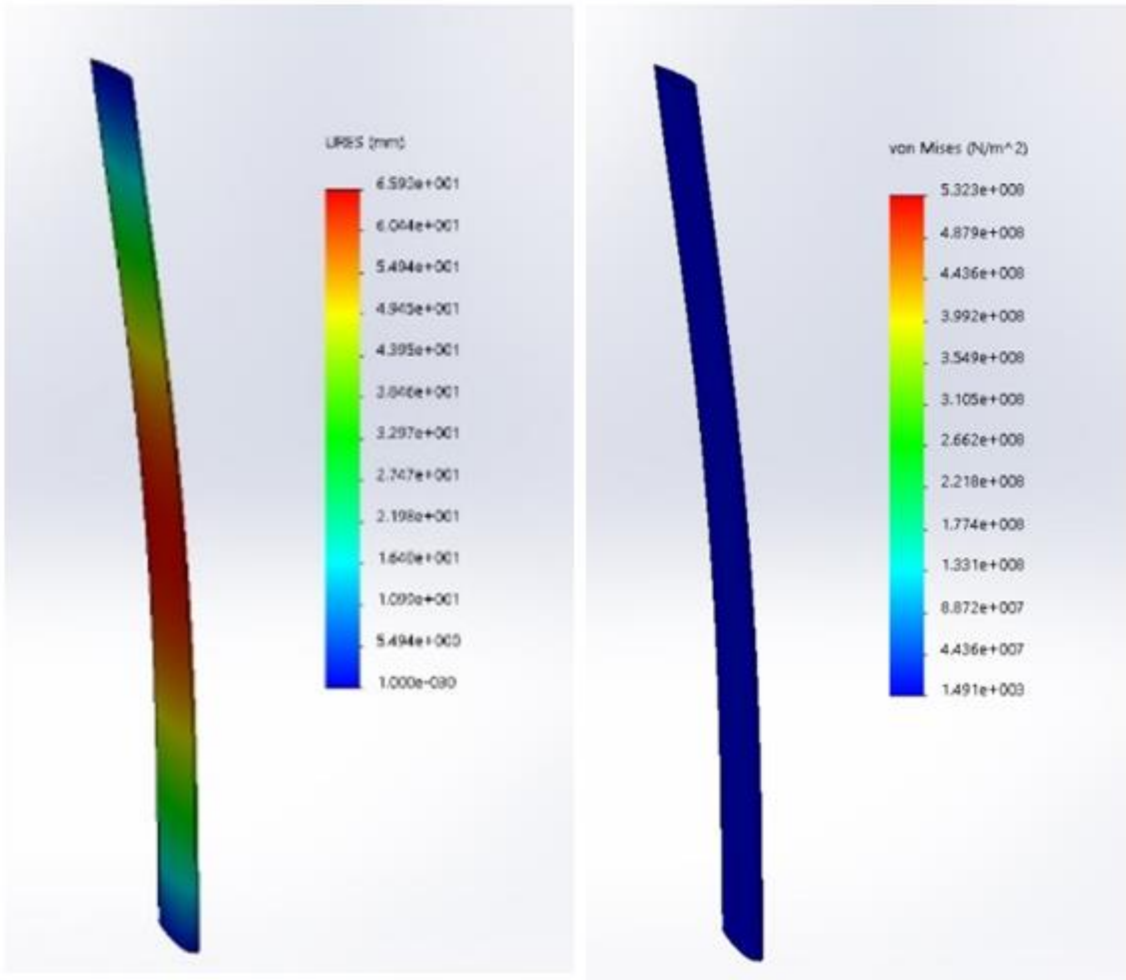


Figure 3.3 Static Analysis of Blade

3.2.2 Shaft

The total displamenct occured in the shaft is 6.054×10^{-3} mm is a good result. The analysis were made considering hardest scenerios and according to analysis, shaft could stand functional however for higher safety, some changes could be made in design such as decreasing the length, changin the material of the shaft etc. In this design the stress in the shaft not exceeds 250 MPa, which is acceptable.

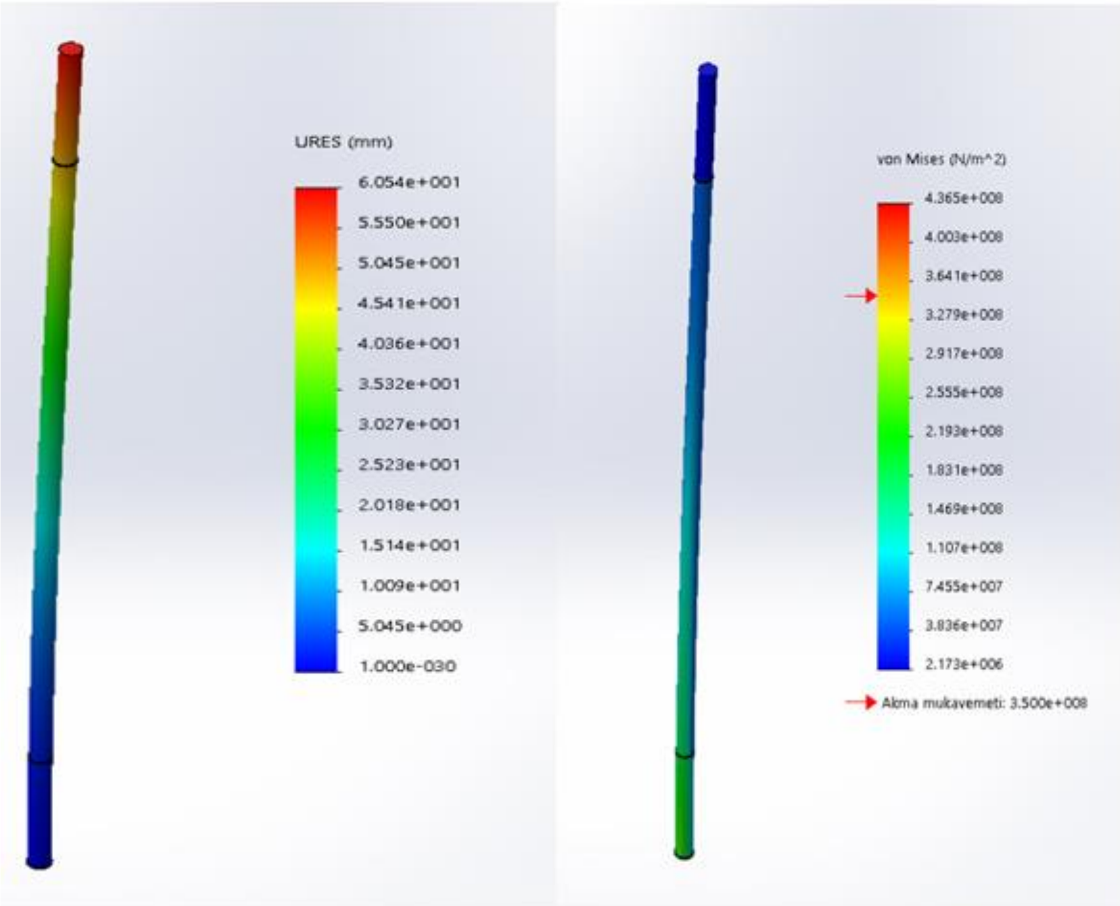


Figure 3.4 Static Analysis of Shaft

3.2.3 Struts

Normally in VAWT, the maximum total thrust is the summation of the thrusts on 3 blades but in this design for safety and durability, it is aimed for struts to carry all the total thrust individually. The displacement and stress constenration are in acceptable range.

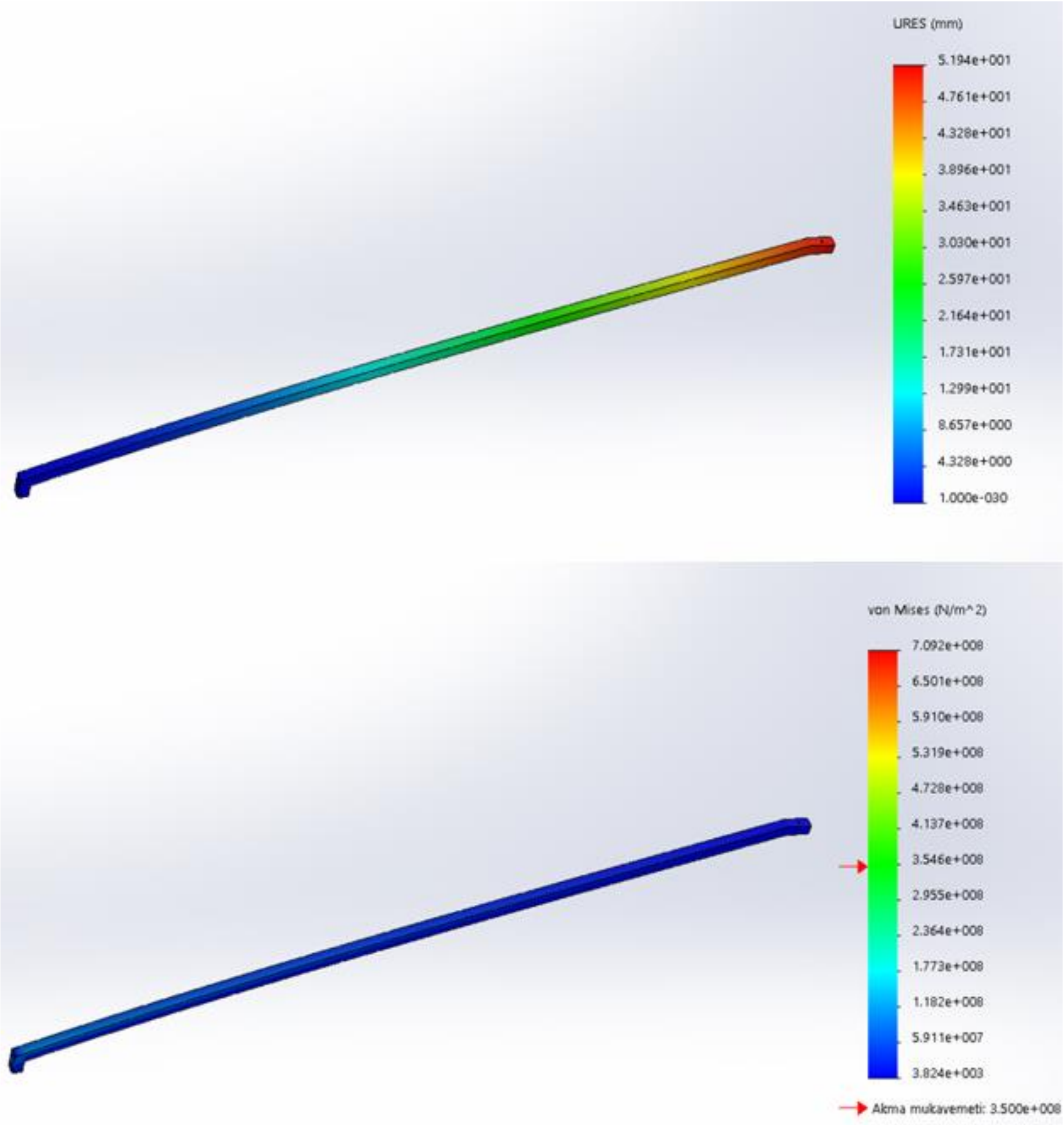


Figure 3.5 Static Analysis of Struts

3.2.4 Tower

For turbines, especially in public places, safety is one of the most important things. The tower is a column for turbine and it should be design under high safety factors. 1.72 mm displacement and maximum 10 MPa of stress on the tower while the tensile strength is 350 MPa can be accepted as a good result.

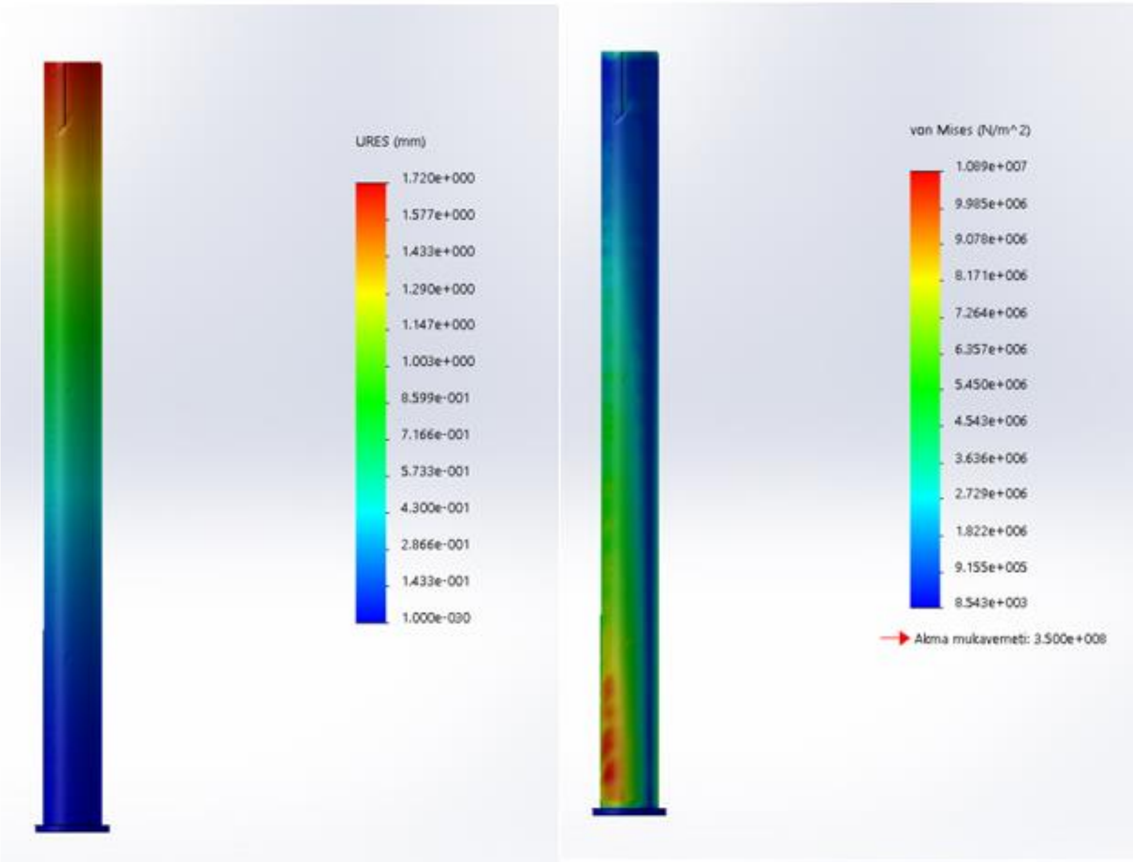


Figure 3.6 Static Analysis of Tower

3.3 Performance Analysis

The lift and drag ratio is the lift generated by aerofoil divided by the aerodynamic drag and it can be called as aerodynamic efficiency too. Higher lift and drag ratio means higher efficiency. It varies due to positon and angle of the blades and it has peaks points, shown in Figure 3.7.

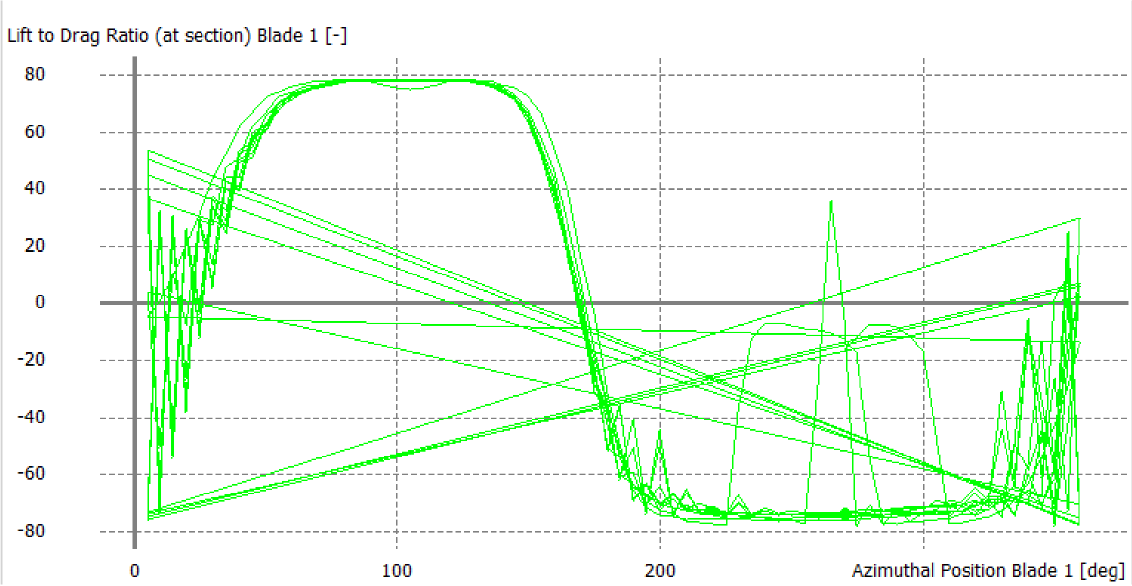


Figure 3.7 Lift to Drag Ratio - Azimuthal Angle Curve

The average power output is higher than the turbine capacity according to analysis. It is occured becaused of the dynamic stall phenomenon mentioned before. The time range for the analysis is 5 seconds and it reaches steady state by the time. In this analysis, the mechanical and electrical losses are not included.

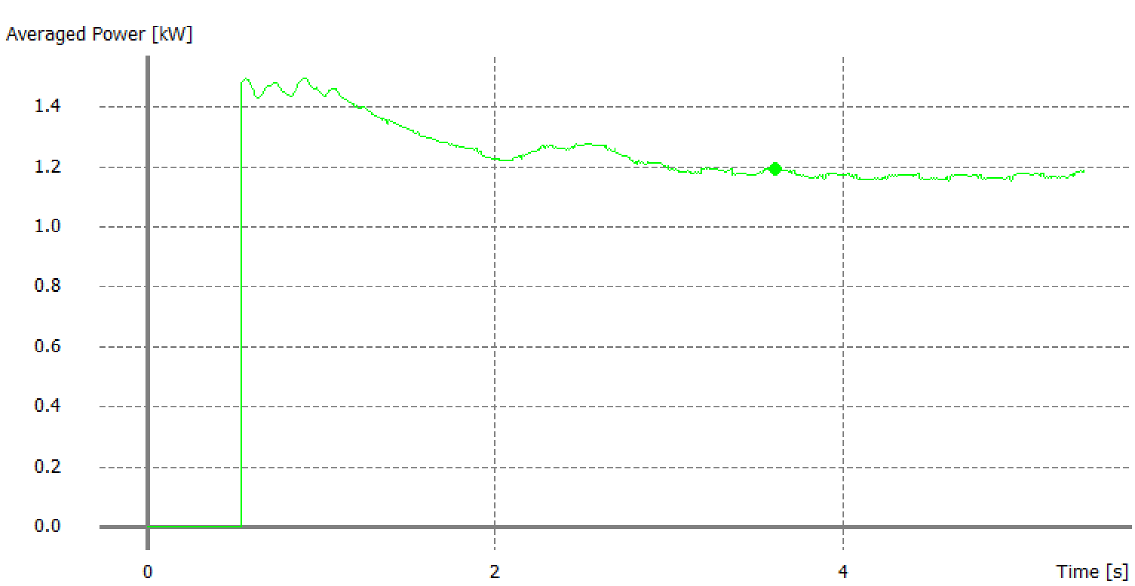


Figure 3.8 Averaged Power Curve

The average thrust is the average forces on blades and it is helpful for static calculations. It is vectoral summation of total tangential and normal forces. Average torque is related with the rotation of the turbine so it directly effects the efficiency of the turbine. As expected, both thrust and torque are effected by the dynamic stall.

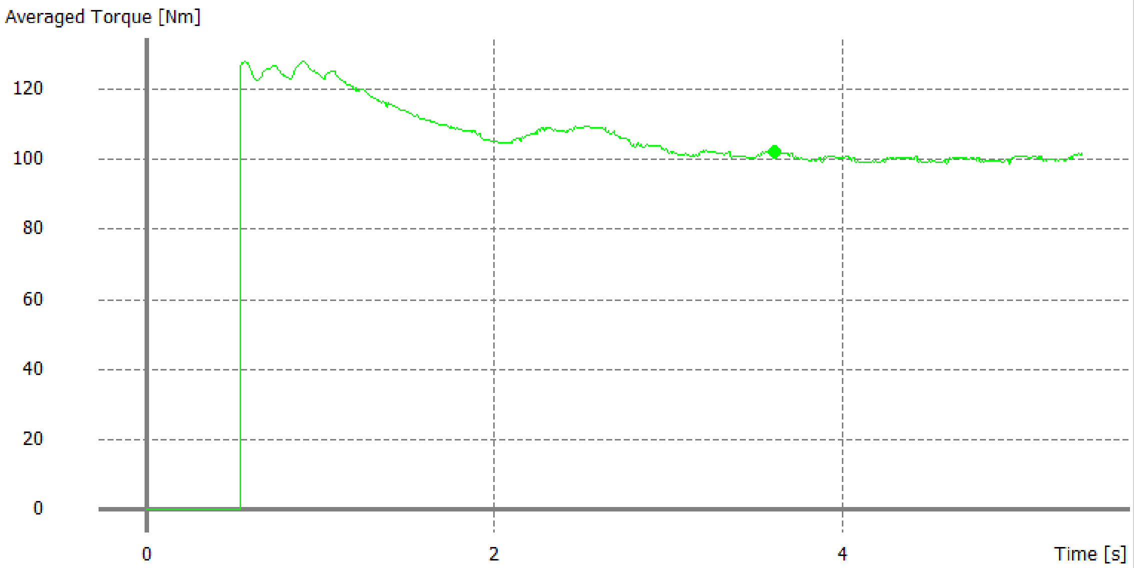


Figure 3.9 Averaged Torque Curve

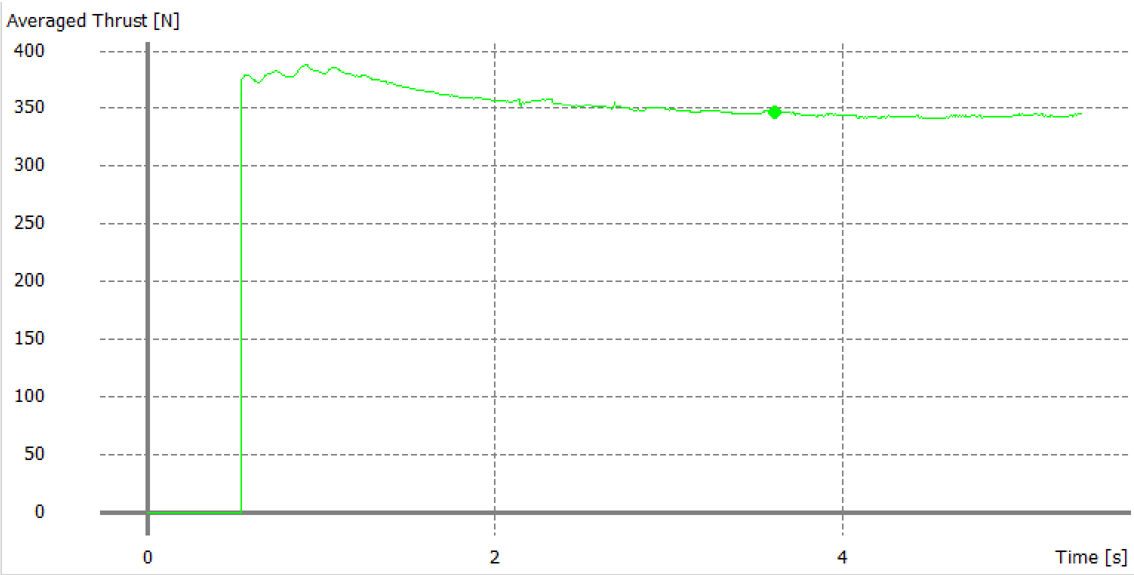


Figure 3.10 Averaged Thrust Curve

3.4 COST ANALYSIS

The cost analysis is an important parameter to show how economical the design is. Two different methods were used for cost analysis.In the first method, the prices of the parts in the market in suitable scales for our design are directly taken from the websites of the companies. In the second method, mathematical functions created by using historical statistical data for wind turbine designs were used. In these functions, certain parameters of the turbine we designed were used. In both methods, prices were calculated in dollars.The annual operating and maintenance cost, which is another cost item, is stated to be between 1.5% and 3% of the original cost of the turbine, according to the data of the Danish Wind Industry Association.In both methods, prices were calculated in dollars. [14,15,16,17]

Rotor Blade Cost

The cost of a composite wing is calculated based on its height, and our cost is in dollars.[1]

$$Cost_{wing} = 3.1225L^{2.879} = 3.1225(3.1)^{2.879} = 81x3 = 243$$

3.4.1 Link Rod

We will calculate the cost of the rods used to connect the blades to the shaft. The rods are selected as AISI 1020 cold drawn. Their costs are taken as the basis of their dimensons. The dimensions of the square steel bar are 30mmx30mm and the length is 2.3 m. The price of one is $9.32.We need 6 of them. The price is taken from the website of steel companies.[18,19]

3.4.2 Shaft

The shaft is in the form of a round bar. The bars are selected as AISI 1020 cold drawn. Their costs are based on their dimensons. The prices of the round bar are 25mm in diameter and 5.25 m in length. The length of the shaft is the distance between the top of the tower center and the generator. The price is $15.30 in dollar terms. The price is taken from the website of steel companies.[18,19]

3.4.3 Tower

The shaft is in the form of a round tube. The tube are selected as AISI 1020 cold drawn. Their costs are based on their dimensons. The prices of the round tube are 304mm in outside diameter and 2 mm in wall. The price is $101.89 in dollar terms. The price is taken from the website of steel companies.[18,19]

3.4.4 Bearings

The price of a tapered roller bearing in the desired dimensions was calculated by taking the average price of 3 sites.

3.4.5 Generators

The generator we are looking for is direct-drive, 1 kw permanent magnet generator for vertical axis wind turbine. However, it comes from China and its price ranges between $600 and $800. And we will take the average of these.[20]

3.4.6 Electrical Connections Cost

$$Cost = 40(Power) = 40(1) = 40$$

3.4.7 Assembly and Installation Cost

When correlating historical factors related to installation cost, the two most important wind turbine design parameters were found to be hub height and rotor diameter.[21]

$$Cost = 1.965[(HubHeight)(RotorDiameter)]^{1.1736} = 1.965[(5.5)(4.2)]^{1.1736}$$
$$= 78.3$$

3.4.8 Electrical Interface/connecitons Cost

The Electrical Interface connection cost is calculated as the cost of the cables going from the wind turbine to the transformer center.[14]

$$Cost = 3.49x10^{-6}(Power)^2 - 0.0221(Power) + 109.7$$
$$= 3.49x10^{-6}(1)^2 - 0.0221(1) + 109.7 = 109.7$$

Table 3.1 Cost of the Wind Turbine Design

Part Name	Material or Type	Number or Amount	Cost ($)
Rotor Blades	**Composite**	**3**	**243**
Link Rod	**AISI 1020 Cold Drawn**	**6**	**55.98**
Shaft	**AISI 1020 Cold Drawn**	**1**	**15.30**
Tower	**AISI 1020 Cold Drawn**	**1**	**101.89**
Bearings	**Tapered Roller**	**1**	**25**

Generator	**Direct-Drive**	**1**	**700**
Electrical Connections Cost			**40**
Assembly and Installation Cost			**78.3**
Electrical Interface/connecitons Cost			**109.7**
Total			**1369.17**

In addition to these, if we take The annual operating and maintenance cost that I mentioned at the beginning as 2 percent and add it above, we will have a total cost of $1396.5.

We will calculate the depreciation period of this wind turbine by dividing this cost by the money we will get from the electricity we produce annually. Prices per unit Kwh are taken from the text written in 2021 for the prepared by the Trade Council of Denmark in Istanbul Wind Energy Market in Turkey.Prices are approximately USD 0.05/kWh with support from domestic producers.[21]

The annual average energy production is 5035 Kwh with calculated Weibull distribution via QBlade.Weibull parameters are k=3 and c=6.86. However, a wind turbine will never produce as much electricity as the ideal energy. We will calculate the electrical and mechanical loses we take %5 of this 5035x95/100=4783kWh. If we multiply this with the unit price of electricity, we get approximately 239 dollars per year. If we divide this by our cost, we find the amortization period as 5.8 years.If we take into account the engineering and labor costs, land rental cost, financing costs, fluctuations in electricity prices, which we ignore while calculating the cost, this will increase even more in 5.8 years.As a result of the analyzes made as a result of the selected samples, it is predicted that a wind power plant will pay for itself in 7-8 years. Considering this, it is thought that the cost analysis we calculated will converge to this.[22]

3.5 ENVIRONMENTAL ANALYSIS

With the increase in energy demand day by day, it is expected that the environmental pollution caused by the electricity sector will increase even more in the coming years. On the other hand, wind energy does not pollute the air or water with harmful gases and substances. It does not produce hazardous wastes that cannot be disposed of safely as in nuclear power plants. For this reason, wind is considered one of the cleanest energy sources available today. If we can make use of even a small portion of this abundant and environmentally friendly energy source, today's energy-related emissions can be reduced to acceptable levels.While generating electricity with existing resources in Turkey, mainly fossil fuels (especially natural gas and coal) are used, and 489 g of CO_2 equivalent greenhouse gas is emitted, from which 1 kWh of electricity is produced.

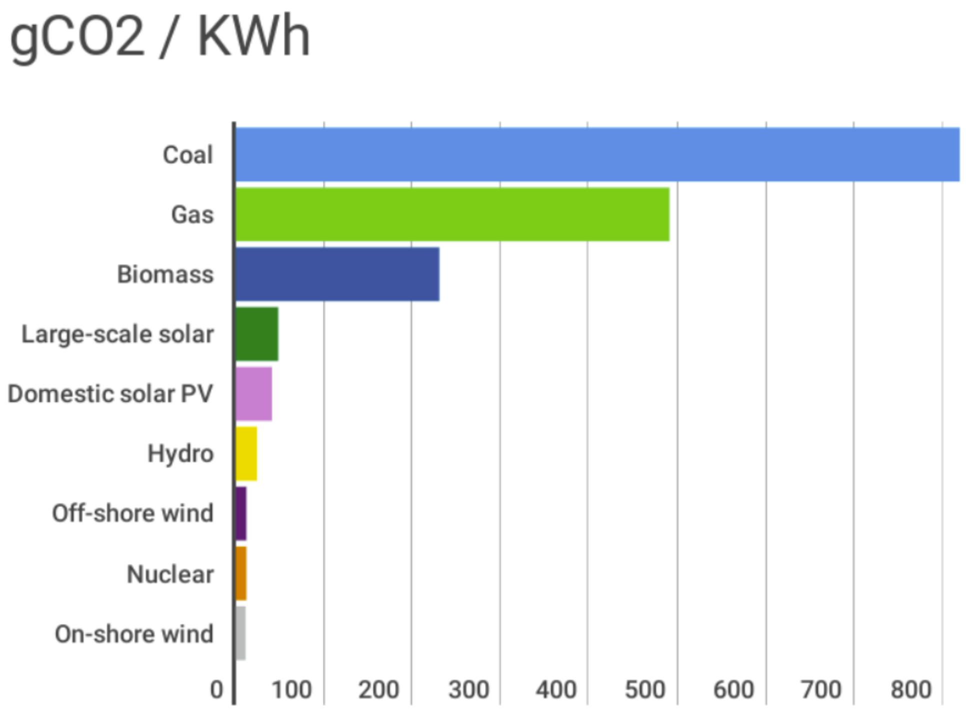


Figure 11 CO_2 **Emissions by source when generating one kWh of electricity source IPCC[23]**

As can be seen from the figure below, a wind turbine on the ground has released an average of 10 g CO_2 carbon emissions for 1 kWh of electrical energy. If we calculate, we reduce carbon emissions by 98 percent thanks to the wind turbine we have made. If we multiply this with our annual production, 0.479x4783=2291 kg CO_2, and if we calculate this with the average life of the wind turbines, 2291x20=45821 kg CO_2, that is, we will have released approximately 46 tons less CO_2 to the environment thanks to the wind turbine we produce.[24]

Completion of the material cycle with wind turbine recycling; It has a positive effect on the use of natural resources, emissions and energy use. Completion of the material cycle can be explained as the conversion of wind turbine blades produced from scratch to the raw material of another product by recycling. Energy requirements for processed and recycled materials are generally lower than for untreated materials. However, some materials or structures such as wings may lose quality after recycling. Approximately 70% of the impact of wind energy use on the environment is due to the materials used in the production of turbines. For this reason, ensuring optimum recycling at the end of the service life is economically and environmentally important. Recycling of wind turbines at the end of their service life, in addition to significant environmental benefits, reduces the use of natural resources and ensures the future use of resources. Recycling, reusing and reprocessing critical materials such as steel, copper, rare earth magnets and glass fiber will reduce overall global resource consumption and address unexpected market changes such as supply shortages. Three types of waste are predicton in our design, first of all we use excess waste after the turbine life cycle is complete. Steel, on the other hand, does not have a problem in terms of waste management in any way, it is used by remelting and leaves us an income. Another type is the blades we use, these are composite and today turbine blades are used as fuel in cement factories. Separation is very possible, at least industrially. The last one is the direct-drive generator that we use. These generators, on the other hand, can pose a danger if left to nature. Thanks to the precious metals and natural magnets used in them, they have an economic value, and they are sold in both environmental and environmental protection. not only does it have a profit, it also has an economic return.

3.6 Feasebility Analysis

Feasibility analysis is whether a project that is at the idea stage is economically, technically and financially viable in real life. From a technical point of view, there does not seem to be a big problem in the execution of the project. Of course, there will be problems and corrections during the project. However, when this project is examined from a technical perspective, especially its dimensions I don't think it will cause a big problem in terms of business. Another point is that if permissions and procedures cause problems, the fact that the area to be considered is within the university and will be used for research shows that these problems can be easily overcome. According to calculations, the fact that the project pays for itself makes it economically applicable.From a financial point of view, a cost of $1400 seems to be a cost that the university can afford. So this wind turbine can be implemented in real life.

3.7 Safety Analysis

While performing the safety analysis, an analysis was made with the help of Solidworks whether the turbine's tower could be lifted or not. It was determined that the mast was tilted against the load. We determined the wind turbine as the roof of the university building, where we will place it. Which building is more reliable can be determined by the university's own occupational health and safety experts. If desired, the wind turbine can be fixed to the ground with ropes to the roof. Considering the building heights are estimated between 10-15 meters, it is not a big threat to aircraft, but a light can be placed on a top of it. The small size of the turbine is an important criterion for safety, and being on the ground makes it more reliable as the center of gravity is closer to the ground.

4 CONCLUSION

As a result of this research, if we divide the research into three parts, these are the research of the speed distribution of the wind in the first part, the type and design of the wind turbine in the second part, and the analysis in the third part.

First, we chose a region close to Marmara University campus. We used the Global wind atlas site for the data of this region. A dominant wind direction was examined and a prevailing wind direction between 10 and 45 degrees was assigned. The hourly distribution was examined and it was observed that the wind speed decreased in the morning hours and increased towards the evening hours. Hourly and monthly wind speeds were calculated using the average wind speed. Average wind speed is 6.13 m/s2 .The wind speed distribution we have has been adapted to the most widely used bivariate weibull distribution in this field. We graphed it using the Weibull distribution. From this graph, we chose the fitting shape factor as 3 and the scale factor as 6.86, which is most suitable for our wind speed. And we plotted the power density graphs with this. And we plotted the wind power potential of the region we chose to wind.

In the second part, the wind turbine type was evaluated in terms of suitability for the region. And the Vertical axis Wind turbine, which was seen as the most suitable, was selected. The reason for this was that this turbine type was cost-effective and showed better performance at low wind speeds. Later, a wind turbine was designed with the help of Solidworks. Wind turbine dimensions are designed to obtain 1kWh power by taking the average wind speed as a reference. According to Betz's law, some of the energy considered in the design is lost. Appropriate blade profile was examined and NACA-0018 was preferred. Then, aerolelastic effects were examined using the Qblade program.While designing, we both used our engineering knowledge and improved it in many ways.

In the third part, 6 analyzes were made, these are structural, performance, cost, environment, feasibility, and safety analyzes.Structural analysis The physical durability of the turbine parts was examined using Solidworks and no problems were detected. Performance analysis The performance of the turbine we designed using Qblade was tested. Power, thrust, and torque curves were calculated. And no fundamental problems were encountered. In the cost analysis, the installation cost of the turbine was calculated. If the products were available in the market first, the price was taken. If the product could not be found in the market, the price was determined using mathematical functions created using historical data. We calculated the annual average energy production using the Weibull distribution for the price we determined. And the amortization period of the project was calculated. Our calculation was 5.6 years. Of course, this is the minimum years, we can predict that it will increase. Environmental analysis, we calculated how much our carbon footprint will be reduced thanks to the wind turbine we produced. And after completing the life of the turbine's parts, the effect on the environment was examined. All these data are available. A feasibility analysis was also made by using it. And the feasibility of this project was analyzed. Finally, the safety of the turbine was analyzed and no problem was detected.

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