DESIGN AND FABRICATION OF A ROADSIDE VERTICAL AXIS WIND TURBINE

A Final Year Project Report

Presented to

SCHOOL OF MECHANICAL & MANUFACTURING ENGINEERING

Department of Mechanical Engineering

NUST

ISLAMABAD, PAKISTAN

In Fulfillment

of the Requirements for the Degree of

Bachelor of Mechanical Engineering

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ABSTRACT

The report consists of a detailed discussion and tabulation of the final year project subjected to the Design and Fabrication of a roadside Vertical Axis Wind Turbine (VAWT) in the partial fulfillment of the bachelor's degree at the School of Mechanical and Manufacturing Engineering (SMME), NUST, H-12, Islamabad. Keeping in view the clean energy demands of the modern world, the project is focused on the design, fabrication, and efficiency boost of the VAWT. The location of the turbine is projected to be roadside which is the main consideration for design and simulations. The small-scale prototype model is prepared after detailed parametric studies, mathematical calculations, design studies, simulations, and experimental testing, all of which are discussed in the report comprehensively. Electrical Energy generated from the roadside turbine due to gust vortices is used to meet small-scale requirements in urban highways or nearby areas. Different anchors of vehicle size, blade height, turbine position, wind speed, and vehicle speed were used during calculations, simulations, and Q-blade studies to achieve a design that is more robust and efficient both in terms of cut-in speed and efficiency.

ACKNOWLEDGMENTS

We would like to acknowledge the efforts of Dr. Emad-ud-din for recognizing our potential in us and accepting our proposal. Moreover, the help and the direction which Dr. Adeel Javed provided us in our journey are also laudable.

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ABBREVIATIONS

TSR	Tip Speed Ratio
NACA	National Advisory Committee for Aeronautics
CFD	Computational Fluid Dynamics
SMME	School of Mechanical & Manufacturing Engineering
VAWT	Vertical Axis Wind Turbine
HAWT	Horizontal Axis Wind Turbine

NOMENCLATURE

C_p	Performance Coefficient
C_q	Torque Coefficient
C	Chord Length
P	Power (W)
N	No. of Blades
α	Angle of attack
σ	Solidity
ω	Rotational velocity
C_d	Drag Coefficient
C_L	Lift Coefficient
A	Swept Area
V	Velocity
l	Blade length
N	Number of blades
P	Power
λ	Tip Speed Ratio

Chapter 1: Introduction

With the advent of science and technology, everything changed, as time passes there came a revolutionary change in technology. We saw that in the blink of an eye, new methods of energy harvesting were discovered. People are now believing in more advanced methods having less execution time. In the industry medieval era of Europe in the 18th century, we have seen the conventional methods were used but it was big advancement at that time. Nowadays major work is being done on how to make machines cost-effective, maintenance-free with higher efficiency. At present energy from renewables attracts the attention of a lot of scientists but it is also noticed that the resources are depleting day by day, for instance, taking the example of coal, and natural oil/gas, these resources are inadequate so now it's time to shift toward never-ending resources like wind energy, solar energy, and energy from water. Wind energy is considered a clean and green source for producing electricity. To harness wind energy, we need wind turbines that convert wind kinetic energy to electrical energy. The subsequent discussion is on wind turbine types, designs, and methodology to form electricity from wind.

1.1 Wind Turbines

Wind energy is an efficient source of energy, to extract wind energy we need a wind turbine that converts wind kinetic energy into mechanical energy that can be transformed into electricity using a generator.

1.1.1 Types of Wind Turbines

Wind turbines are generally classified on various principles like turbines which differentiate from one another on basis of the axis of rotation of the rotor are,

1.1.2 Vertical axis wind turbine (VAWT).

It is a type of wind turbine in which the wind direction is transverse to the rotor blade while the main components are located at the base of VAWT.

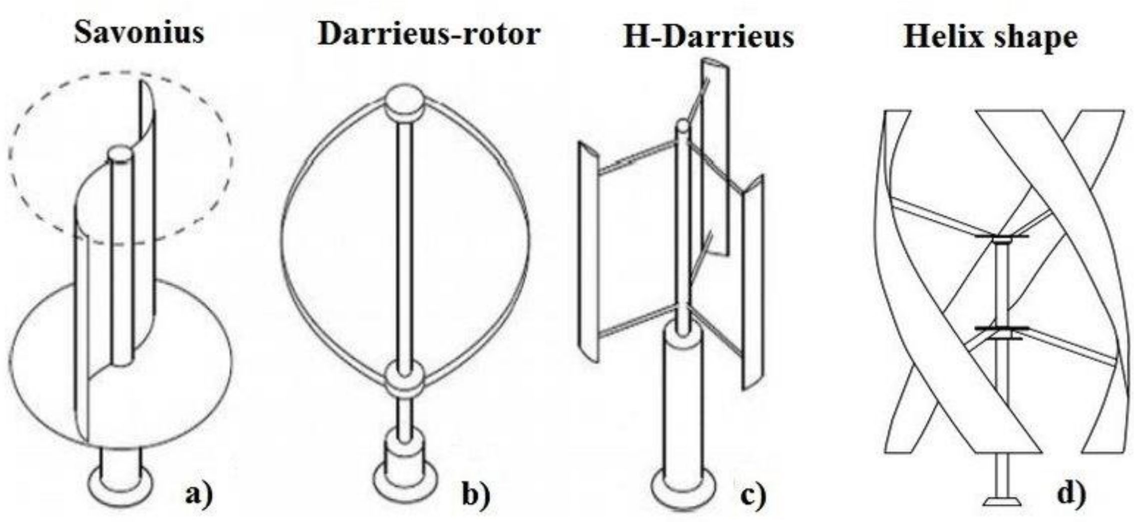
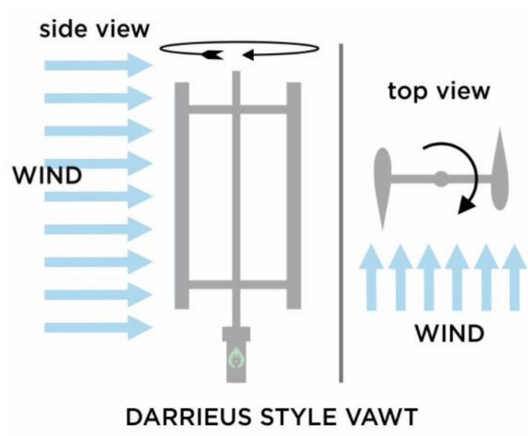


Figure 1: Turbine Configurations

Vertical axis wind turbines are also classified on basis of torque generation mechanism either by lift or drag force.

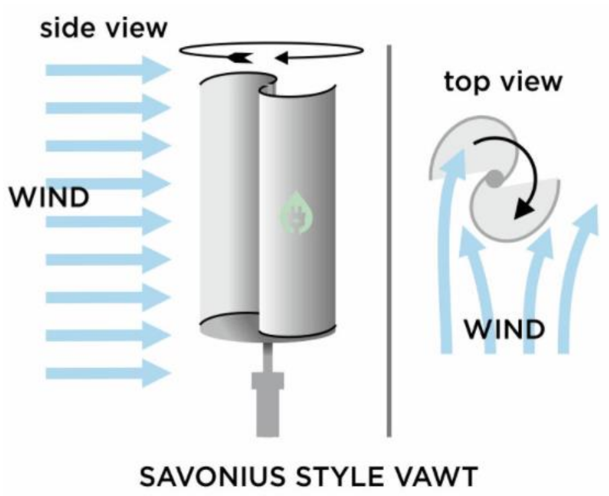
1.1.3 Darrieus wind turbine.

It is a lift-based vertical axis wind turbine that rotates the rotor by developing pressure difference on each side of a blade, this pressure difference exerts a force that causes the rotor to rotate. The blades of Darrieus type wind turbine are similar to airplane wings and the mechanism of pressure difference and lift force is also the same.



1.1.4 Savonius wind turbine.

Savonius wind turbine uses the principle of drag to convert the kinetic energy of wind to generate electricity. It is scoop-shaped that traps the wind to create enough drag force which in turn rotates the turbine. These types also have certain limitations like the wind force act on every blade of the turbine so on one side it causes the blade to rotate but on another side, it hinders the motion which is why such type of VAWT has reduced efficiency.



1.1.5 Horizontal axis wind turbine (HAWT).

It is a type of wind turbine in which the wind direction is parallel to the axis of the rotor blade while the main components are enclosed in a nacelle. HAWT can be formed from a single blade or **multi-blade** structure but most commonly a HAWT has three blades attached to a rotor that give optimum results.

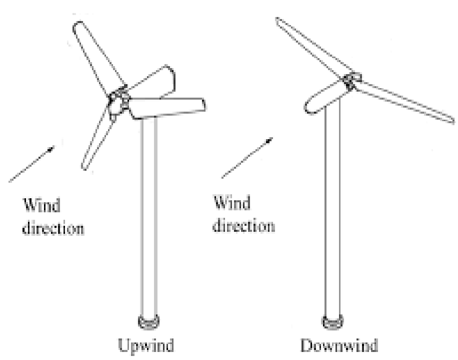


Figure 3: Horizontal Axis Wind Turbine

1.2 Components of Our Wind Turbine

The wind turbine has the following main components,

- Rotor
- Nacelle
- Foundation and Tower
- Generator
- Starting mechanism
- Adjustable Slats

1.2.1 Rotor

It is the main rotating part of a wind turbine; blades are attached to a rotor and the number of blades can be varied but the most efficient rotor has three blades attached. Blades are made of composite materials and the main objective is to make them large, lightweight, and strong to harness maximum wind energy. Since we are working on a lift base turbine, we are using NACA 0018 profile as it has been proven for the maximum performance efficiency in Darrieus turbines. The rotor is connected to a shaft via the hub and connecting rods. The shaft turns the generator to transform mechanical energy into electrical energy which can then be transmitted to the required locations.

1.2.2 Nacelle

It is a housing that contains all the components of an electromechanical system that are used to convert mechanical energy into electrical energy. The gearbox is one of the most important components present in the nacelle that increases the rpm of a turbine in a range of 12-25 rpm. In HAWT nacelle also has a yaw mechanism. The nacelle in the VAWT is on the ground in contrast with the HAWT in which the nacelle mechanism is mounted on top which makes it difficult to maintain and troubleshoot in case of a fault.

1.2.3 Foundation and Tower

Foundation is used to sustain the load of the whole structure of a turbine ensuring the structural integrity of the turbine. A tower is usually a hollow tube through which the shaft is passing.

1.2.4 Generator

It is the major component that produces electricity from mechanical energy. It has the same structure as an electric motor.

1.2.5 Starting Mechanism

The starting mechanism is essential for the working of VAWT as the initial torque required is higher than that provided by the wind. Once started, inertia starts to play its role and the system becomes self-sufficient. It can be compared to the spark plug of a gasoline ICE. The starting mechanism is incorporated with the generator assembly and can be used by the controlled manipulation of the output which is managed using a control algorithm.

1.2.6 Adjustable Slats

This component can be regarded as the defining novelty factor in our project that makes it different from the already existing models made through the existing research. The overall efficiency of a VAWT is challenged and ultimately lowered due to multiple factors. So, to minimize this effect, we have decided to introduce an advancement of adjustable slats to our project which is still under study worldwide. The slats delay the wake formation on the turbine blades and as a result, they reduce the cut-in speed and increase the turbine power.

Slats are smaller airfoil blades generally made of smooth profile lightweight materials like PLA, or Aluminum, which are attached to the leading edge of the turbine blades.

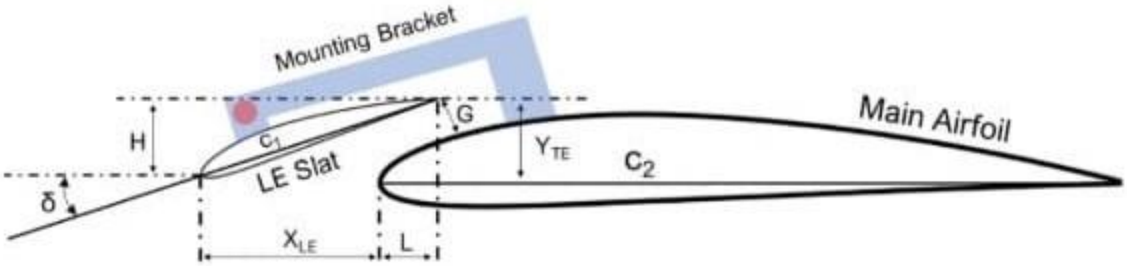


Figure 4: Slats on VAWT Blades

1.2.7 CFD

The main objective of performing the computational fluid dynamics was to see the effect of delayed separation on the VAWT baseline. It also revealed information about the optimal leading slat angle for low-speed turbines.

The unique concept of slats was being tested using computational fluid dynamics to prove the veracity of this concept. It was easy to predict using an intuitive Knowledge of engineering what the outcome would be. But to prove the face, we took the help of Ansys.

First, we simulated normal conditions with a normal airfoil's top view. Later, we added slats and conducted the same process. Slats were added on the leading, trailing, and both the edges to see the effect of free wind on the turbine.

Conditions of this test were kept normal with the wind speed of 6 meters per second, and triangular meshing was done for better results. Velocity and pressure contours were noted which revealed useful information about the power generation and efficiency increase due to slats.

The results were then used to reckon the overall model of our turbine; helped us in different areas of manufacturing, and overall hinted about its power generation capability.

The simulation was done by mounting the slats at different locations on the blade. These positions include:

- Offset Slats
- Blade Surface Slats

Tests were conducted on the offset case to achieve the optimized location for the slats.

1.2.7.1 Offset Slats

The best suitable results were shown by the offset slats concept. In this concept, slats were installed at some distance from the blades on either the leading or trailing edge. After that, the turbine was operated.

Offset slats are further subdivided into the following categories:

- Leading Edge Offset
- Trailing-Edge Offset
- Dual Edge Offset

1.2.7.2 Leading Edge offset:

The technique of delaying the flow separation was done by installing the slats on the leading edge of the blade. In this way, the wind gust coming from the trailing edge imparts drag to the turbine and delays the flow separation after interacting with the slat.

The concept worked based on the fact that when airflow interacts with the blades, it splits into two regions. One region of the flow goes out of the boundary layer from the outer side of the blade, and one is infused inside the layer. One which goes inside can be utilized by the blades, and the one which goes outside is further made to interact with the offset slat. This slat further pushes the part of this airflow back into the inner circle and in this way, the overall performance of the turbine is increased.

Figure 5: Slats Leading Edge

1.2.7.3 Trailing-Edge Offset Slat:

Figure 6: Slats Trailing Edge

In this mechanism, slats were installed at the trailing edge, but the results have shown that it has not shown promising results. It is because it disturbs the normal trajectory of the flow at the start of the operation which does not contribute to increasing the lift coefficient. The results revealed by the CFD have been shown here:

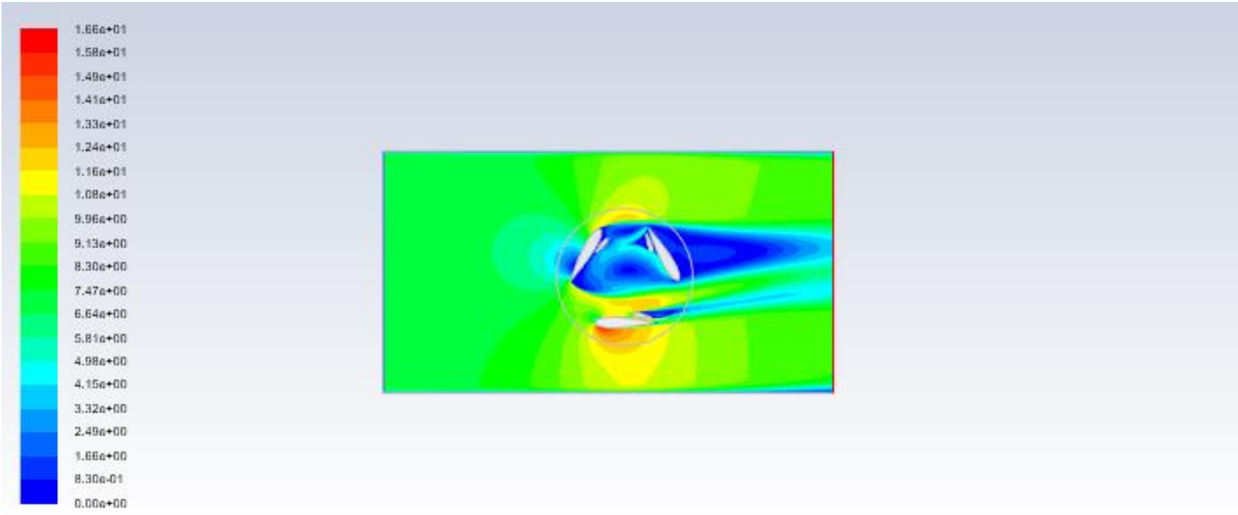


Figure 7: Simulation with Slats

1.2.7.4 Dual Edge Offset Slat:

Figure 8: Dual Edge Slats

Slats on both sides were installed in this mechanism. The results revealed that it increased the drag to the extent that it disturbed the power output by drastically decreasing the rpm. As shown in the attached CFD model, the slats on both sides are delaying the flow separation but at the same time, a considerable decrease in the rpm due to an increase in the drag was experienced during its experimentation.

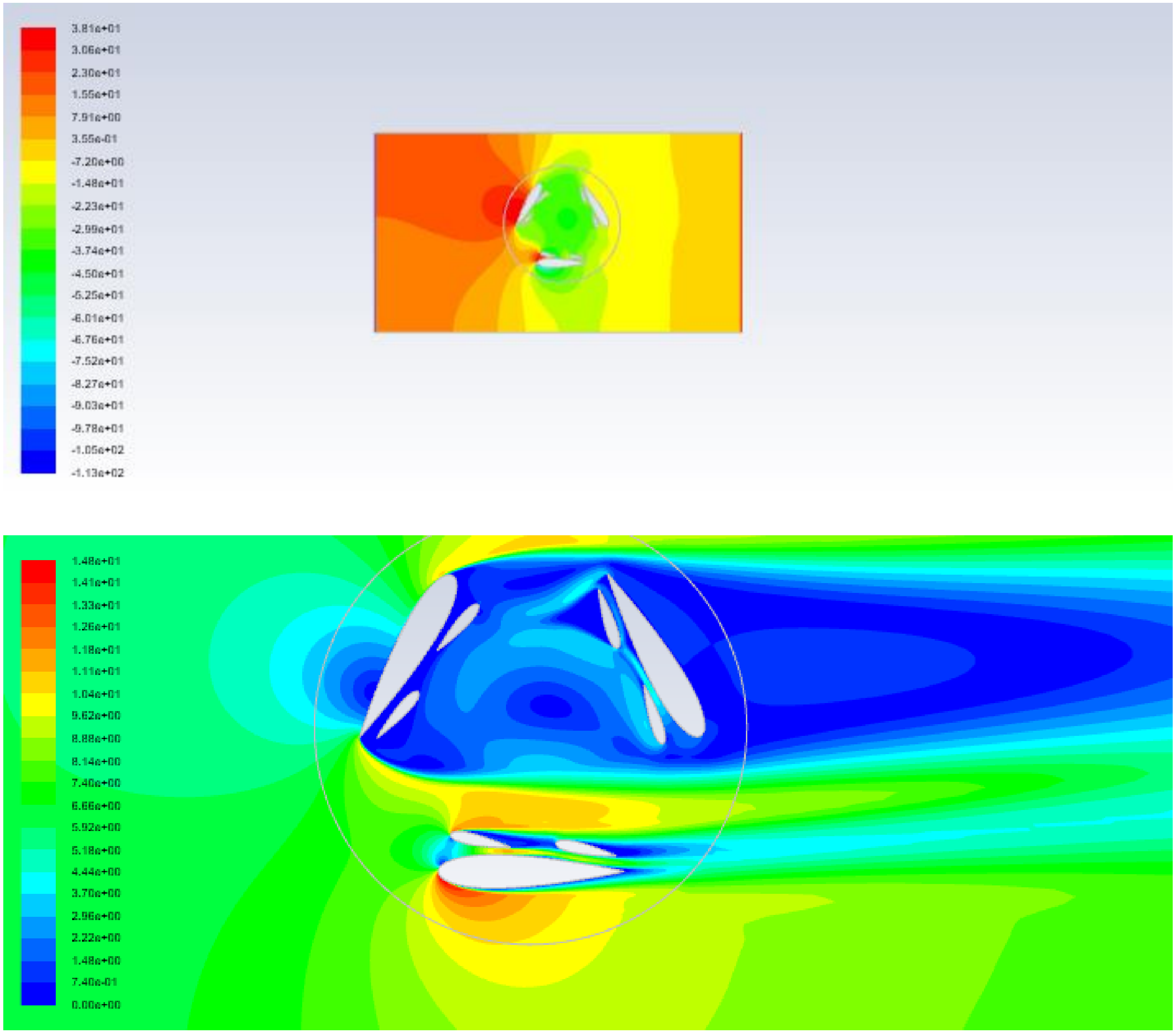


Figure 9: Dual Edge Slats Simulation

Above two shown are the pressure and velocity contours respectively.

1.2.7.6 Angle Variation:

After locating the optimized position of the slats, the Slat angle, which is the angle between the two-chord lengths was tested. Different angle variations were done, and tests were conducted to see the maximum possible results which we could have got in the end. The slat angles were varied, and rpm and torque results were obtained. The results on the 45° slat angle revealed the best output. Moreover, the angle variation also introduced us to a very new concept of a hybrid turbine in our Darrieus model. By varying the slat angle, we can increase as well as decrease the torque and the rpm of the turbine. So, this parameter can be adjusted according to the area where the turbine is to be installed.

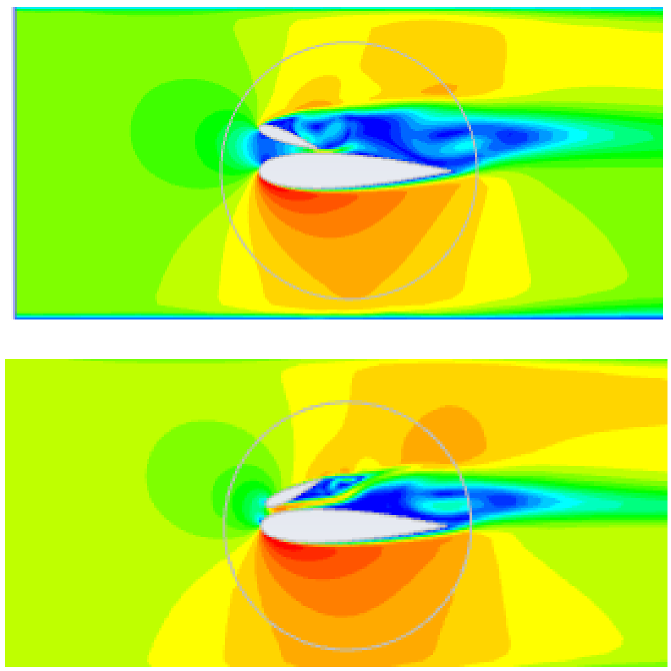


Figure 10: Simulation with Angle Variation

As shown above, the angles of the slats are -45°, 0, and 45° respectively.

12.7.7 Final Selection:

Based on the above models, the final optimized results were shown by the leading-edge offset slats with a slat angle of 45°.

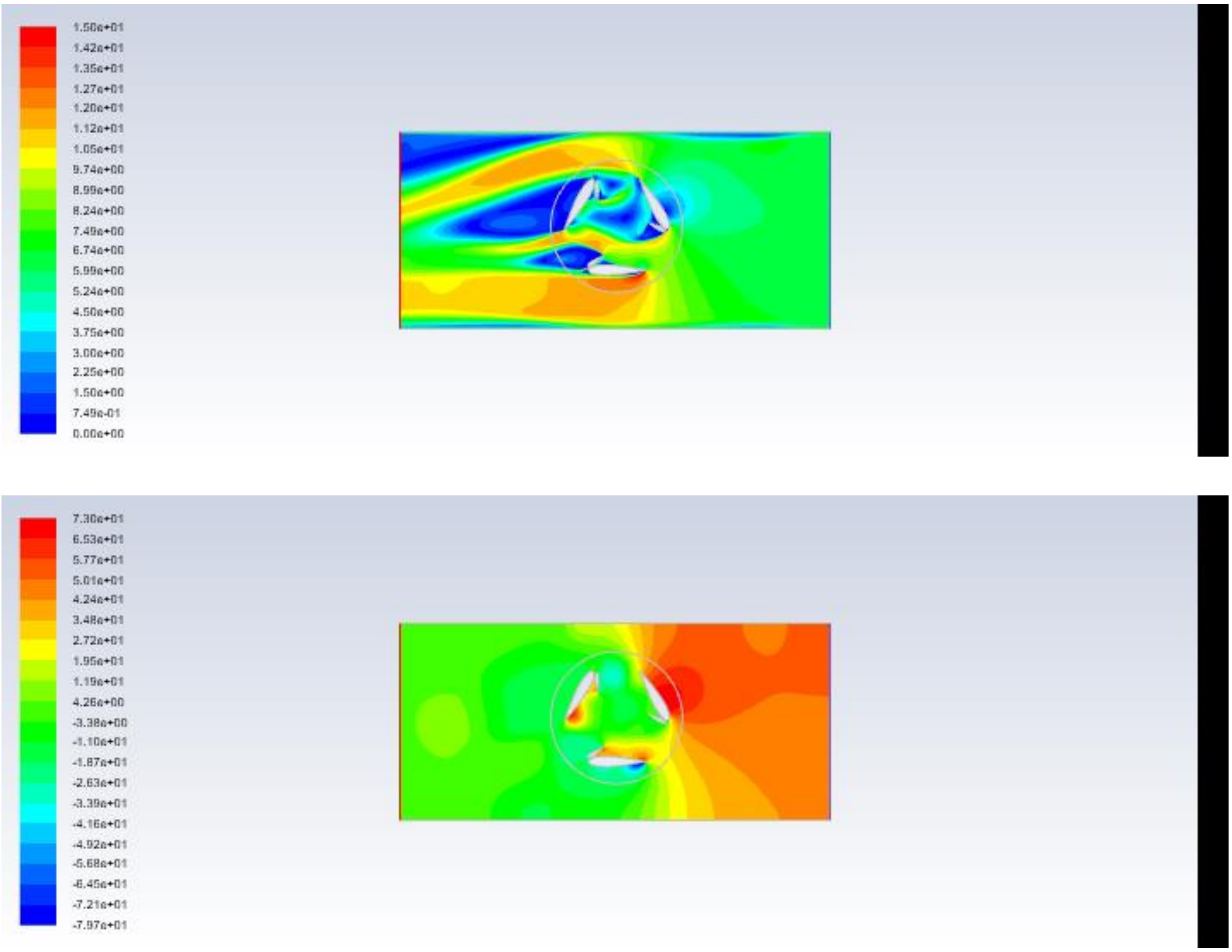


Figure 11: Simulation for finally selected model

Shown above are the velocities and the pressure contours respectively at $6ms^{-1}$. The end effective blade has shown the prominent lift coefficient in the pressure contour whereas, the slat has shown how it redirects the flow inside the area as well in the velocity contour.

1.3 Motivation for Work

1.3.1 Comparison between VAWT & HAWT

VAWT has several advantages that overshow it over HAWT. VAWT is omni direction it can harvest wind energy from every direction making it a viable decision for urban use. VAWT doesn't need any pitch or yaw mechanism for blades and rotors respectively. Horizontal axis wind turbine challenge fatigue stress due to turbulent and gusty wind whereas in the case of VAWT these things become an advantage. In VAWT very low maintenance is required as compared to HAWT because in vertical axis wind turbine major component like gearbox, and power generator is assembled on the base of the turbine which makes it much more convenient for routine maintenance and makes VAWT structure design safer and more robust.

HAWT has greater efficiency than VAWT this is because, in the case of a horizontal axis wind turbine three blades face the wind, and all take part in extracting wind energy whereas in a vertical axis wind turbine only one blade plays a significant role in harnessing wind energy. Another most notable disadvantage of VAWT is the dynamic stall, it is a condition in which separation occurs due to an increase in the angle of attack. In VAWT due to rotation around the vertical axis, there is a continuous change in the angle of attack that results in reduced efficiency along with the induction of noise and structural vibrations.

1.3.2 Insights

1.3.2.1 Pakistani Demographics

Considering the region of Pakistan where we have to face a lot of issues including the security of the turbine and the extreme climatic condition. The concept was not easy to adapt initially. However, research showed that Pakistan aims to shift 60 percent of its electricity to environment-friendly and renewable sources by 2030. Moreover, the startup potential in Pakistan is increasing day by day. Many startups in this region are getting seed funding to nurture their ideas. All these things encouraged us to start thinking about its implementation that would not only allow us to market this project as a potential startup idea but also help us in designing the module according to a Pakistani demographic.

The renewable energy sector in Pakistan is not nurtured at all and seeks a lot of consideration and focus for its development. Pakistan, being a developing nation that goes through energy crises on and off, needs as many sources of clean, replenishable energy as possible. Many efforts are underway in this regard when it comes to the solar and water energy opportunities as is reflected in large water storage reservoir dams including Tarbela and Mangla and the floating solar power plant project in the Tarbela dam. However, wind energy is still an area that has not seen much interest from engineers as well as the government. Keeping in mind this lag and a market gap in terms of opportunity, we have decided to work on a small-scale but productive energy source that utilizes the huge amounts of energy wasted by wind gusts created by vehicles nationwide moving on highways. If more consideration is put into these areas of clean energy, Pakistan can focus on other issues such as global warming and pollution.

Pakistan also holds a vow to the world and being a member of the Paris Climate Accord, has to regularly report its contribution against global warming. Almost 65% of the country's energy comes from non-renewable energy sources which result in huge carbon prints created by the country. However, keeping a low carbon yield is essential for our worldwide image as well as for our citizens.

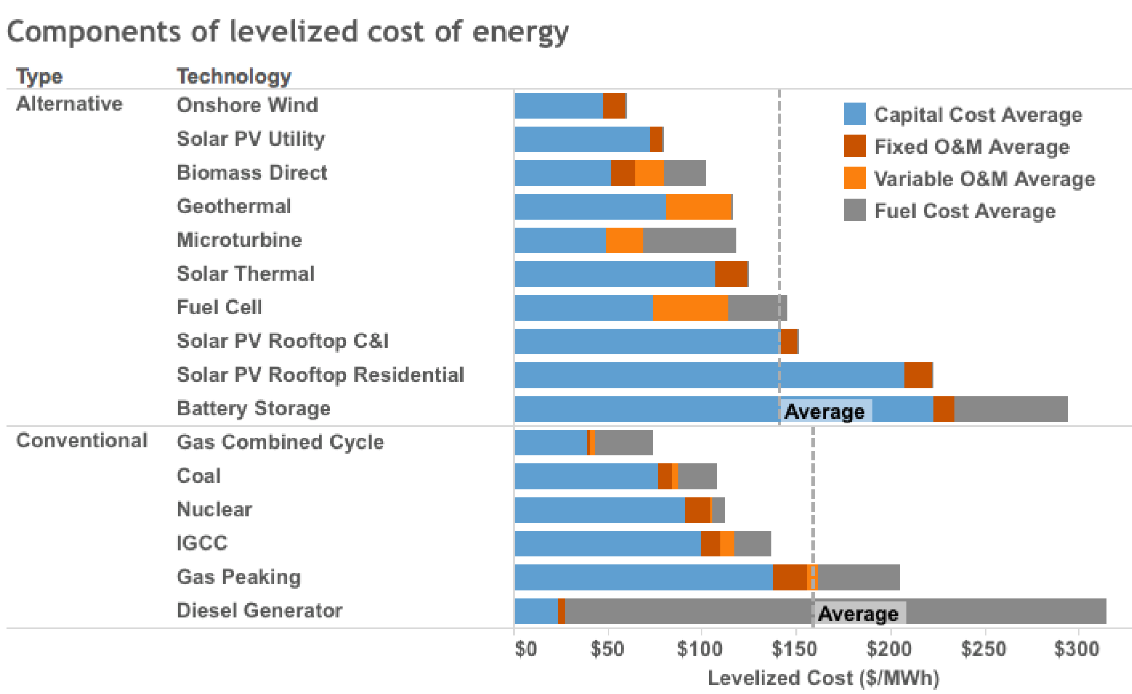


Figure 12: Levelized Cost Insights for different energy types

The Levelized cost shows the financial feasibility of doing a wind energy project against other projects like solar or fossil fuels. Roadside project feasibility, however, is still a long way to be tabulated on a large scale for data as the technology is new and not implemented in a lot of areas yet.

The attention toward wind energy was drawn to the other renewable energy sources in the 1970s after the oil crises worldwide. All the countries of the world became insecure about their position and meeting the energy demands of their public and started considering alternatives. It was further fueled by the nuclear energy power plants incidents such as the world-famous Chernobyl incident in the 1980s. the following table gives an insight into the total wind energy implementation and capacity of several countries as of 2017:

Country	**Installed in 2017**	**Cumulative in Dec 2017**
PR China	19,500	188,232
USA	7,017	89,077
Germany	6,581	56,132
UK	4,270	32,848
India	4,148	23,170
Brazil	2,022	18,872
France	1,694	13,759
Turkey	766	12,763
Mexico	478	12,239
Belgium	467	9,479
Rest of the World	5,630	83,008
Total	**52,573**	**539,581**

Unfortunately, Pakistan was not able to mark a standing among these countries having a cumulative wind energy capacity of 792 MW until 2017. This is one of the key motivations for the students to work on such a project focused on an unattended area of need.

1.4 Important Turbine Efficiency Parameters

In this section, we are going to discuss some important factors that are going to affect the efficiency of our design:

1.4.1 Performance Coefficient

The available potential in wind is dependent on the wind velocity and is determined as:

$$P_{wind} = 1/2\ \rho A V^{3}$$

Where P is the power supplied by wind and ρ is the air density. 'A' is swept area i.e., the area covered by the wings, and V is the velocity of the wind. This is the power available to us, however, a turbine cannot possibly extract 100% of it due to many losses. The possible amount extractable is given by:

$$P_{turbine} = C_p\ P_{wind}$$

C_p stands for the performance coefficient of the rotor and signifies the amount of energy efficiency. The maximum value of the power coefficient is given by the Betz Limit of 0.593 whereas VAWTs typically reach a C_p value of around 0.35.

1.4.2 Tip Speed Ratio

TSR is defined as the ratio of the blade velocity (tip speed of the blade) to the free stream velocity. It is given as:

$$\lambda = \omega R/V$$

In this equation, ω is the angular velocity in rad/s of the blades, R is the radius of the rotor whereas V is the free stream velocity.

1.4.3 Swept Area

The swept area is defined as the amount of area that is covered by the blades and is swept by the incoming free stream wind flow. It is one of the main factors influencing the turbine efficiency and can be increased in several ways including increasing blade length and rotor diameter. However, there is a trade-off as cost also increases with an increase in this factor. It is calculated as:

$$\text{Swept Area} = \pi \times h \times D$$

1.4.4 AirFoil

NACA four-digit foils (particularly NACA 0018) are the best to choose for VAWT. Usually, the thickness of the foil is in the range of 12% to 21% of chord length. The performance of VAWT is influenced by changing the number of blades and most often three blades for the h-Darrieus wind turbine are optimal. If we increase the number of blades beyond three it will induce more drag that hinders the rotation of the turbine. The aspect ratio has its significance as it controls the power coefficient of the turbine. A lower aspect ratio turbine has a higher power coefficient and vice versa. Cambering the blade (giving curvature to the foil) has little to no effect as it increases the tangential force in one direction but on contrary also decreases the force in another half of the total swept area. H-Darrieus turbines have simple geometry because their blades are straight and don't require any yaw mechanism.

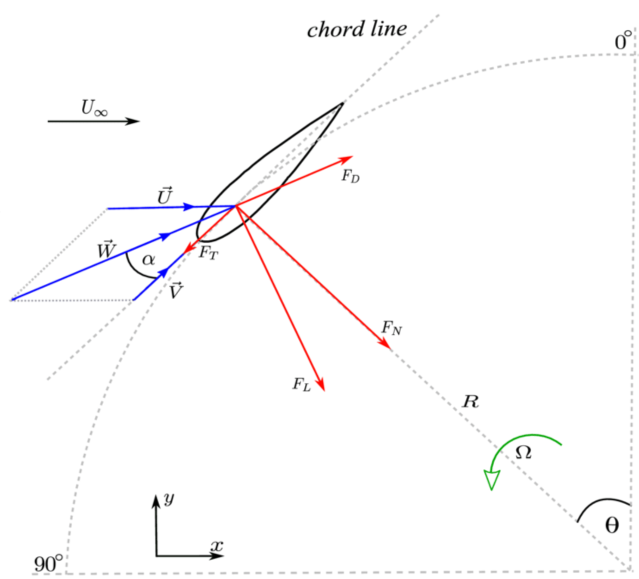


Figure 13: Airfoil force distribution on VAWT

1.4.5 Solidity

It is the developed surface area of the blades divided by the total rotor swept area. This is the key variable that greatly influences the cost and efficiency of a wind turbine. It is defined as:

$$\sigma = N/Cl$$

Where N stands for the number of blades, C is the chord length, and l is the blade length of the turbine.

1.5 Problem Statement

This is where we define the main problem which motivated us to perform this project and what needs to be done to resolve this problem. Roads and streetlights constitute a significant portion of the electricity grid in Pakistan with already a limited amount of energy at hand. This energy chunk can be used in other areas where excessive energy is required. To meet the demand for streetlights and other road utilizes like toll plazas. We can arrange a self-sufficient system that uses energy already available in some form and converts it into electrical energy, basically a renewable energy source. This source can either be a small solar cell or a small wind turbine. The idea is to introduce a grid of wind turbines on roadsides which is backed by certain factors:

- The power conversion efficiency of the solar cells is a lot slower than the wind turbine. That means an increased cost-to-performance ratio by the wind turbine grid if installed with proper consideration. The highest attained efficiency in controlled conditions inside a laboratory is 46% as compared to around 20% average given by a solar source.
- On a good windy day, we can harness wind energy both in light and without light whereas a solar energy source always requires consistent light availability with certain intensity to generate a reasonable amount.
- Urban VAWT can be installed in areas where solar grids are not convenient to be placed. They have a smaller grid size which means they can make more use of smaller space.

These factors affirm and reinforce our decision for going with a wind energy source for our final year project which is going to have healthy prospects if viewed positively by the decision committee and industrial mentors.

1.6 Project Objectives

The object of this project is to harness wind energy by gusts generated on the roadside by creating an unprecedented VAWT model with design advancements that will deliver maximum power and efficiency. If proper funding can be procured, we are aiming for a full-scale ready-to-go model. The objectives can further be enumerated as:

- To do a proper analysis of wind parameters on a selected site (Srinagar highway in our case) to install a dedicated design in place.
- To do proper simulation and parameter study after CAD designing the model.
- To design and manufacture the foundation for the turbine.
- To design and manufacture turbine models and perform structural analysis.
- To install generators available in the market to harness energy.
- Introduce novelty by bringing in adjustable slats (ideally at 16 degrees) to the table to increase efficiency.
- To Introduce a starting mechanism for the optimum model.
- To Perform feasibility studies on the full-fledged prototype and demonstrate improvements.

1.7 Proposed Business Model

The core of this project not only lies in using the engineering knowledge but also in devising a way to commercialize it.

For example, a 100-watt roadside turbine would be a failed model. It increases the size of the turbine which questions the installation on narrow roadsides of Pakistan. It'll eventually collide with it. Moreover, the known history of roads tells us that it would not be safe to mount such an enormous turbine and let the people see and decide what the thing is and how it must be used.

For our turbine, two business models were proposed.

1. Based on the novelty, the designed slat-based system is to be installed on the existing turbines in Pakistan to increase their working efficiency.
2. Model of installing the slat-based turbines in the areas having high wind potential.

1.7.1 First Model:

For our first model, the slats-based system, the market size is limited in Pakistan as VAWTs are not present in large numbers here. However, for manufacturing the proposed business model is as follows:

Purpose	Cost (PKR)
Slats Mould	200,000 -300,000
Material Cost (700-800 g Al)	1000
Labor Cost	1500
Handling Charges	1000
Operations Cost	1000

The mould charges incorporated for a single installation are 2500 PKR. So, the total cost for installing this model will be 7000 PKR. With 30% MOP, it will cost the end customer up to 10,000 PKR.

With the cost of 10,000 PKR, the value proposition is a 20 percent increase in the efficiency of the turbine.

Second Model

Normally, the streetlight power range is 35-50 watts here in Pakistan. So, the proposed model that we devised for this is to install two 20-25 watts designs in Pakistani areas. This will not only adjust the turbines on narrow roadsides across Pakistan but will also lower the cut-in speed for operating the turbine.

In addition, the operating module is better in the areas such as motorways and tunnels because of the improved security condition and the powerful wind gust of a moving car. The idea also stands out in front of solar panels considering their low efficiency during stormy conditions and decreased efficiency during the night.

Table showing the financial comparison to other VAWT:

NAME	POWER (Watts)	COST (PKR)
Curved VAWT	100	150,000
H-Darrieus Turbine	100	100,000
Our VAWT	50	20,000

1.7.2 Commercialization Potential of the Project:

The traffic load in Pakistan is increasing day by day. The power (in terms of wind gusts) generated by the moving cars has been neglected so far. So, to make use of this wind gust, we can commercialize this project.

The potential of a startup in this and providing a viable solution of sustainable energy in Pakistan was also kept in consideration while choosing the design. The design must fit the commercial standard to be installed across Pakistan as well as it should have a novel aspect making it a better performer than the already existing models. For that reason, we met with various startups working on sustainable energy sources and acquired knowledge of the market trends. We brainstormed and kept the commercialization factor in our minds while designing the turbine.

1.7.3 Maximum Efficiency:

The factor of efficiency can considerably be increased by optimizing the design. However, the optimized result cannot ensure the turbine's operation at a very low threshold of approximately $6ms^{-1}$. For that reason, we thought of changing the design distinctively.

In this regard, we took help from the Centre of Advanced Studies & Energy (CASEN – NUST). From there, we came to know about the concept of slats. Slats are the extensions given at the end of the blade to avoid vortex shedding and produce smooth air-blade interaction. The experimental data we accessed showed a drastic increase in the efficiency of VAWT by just doing this simple step.

1.8 Novelty Proposition

Each day we see how new technology makes its ground in our lives. We have seen how the trend in the world has been shifting towards more reliable and efficient ways that lead to innovations.

The roadside vertical axis wind turbine is one of those innovations that created its impact in recent years. This technology has the basic ground in generating energy through wind, but in a way that nobody discussed in the past.

Being comparatively a new technology, it has a large room of novelty where one can find ways of increasing its efficiency. The fact, however, cannot be neglected that this technology has not been implemented in Pakistan yet. So, running the cases based on Pakistan's demographics has undoubtedly provided us the chance to discover new designs that could have sustained here.

Apart from that, we worked on ways of increasing its efficiency as well for which we took the aid of the slated model as described above in the CFD section. A slat is a narrow, airfoil-based strip mounted either on the leading or trailing edge of the main blade. Slats are made of a very light, easy-to-machine material that creates a negligible effect on the weight of the turbine but impacts considerably on the turbine's efficiency. Data in our research showed that it could increase the efficiency up to 18-23 percent.

Considering the curved blade profile of Darrieus Turbines, the slats concept made the efficiency of H-Darrieus turbines nearly equivalent to that of curved blade turbines with 40 percent less cost. This concept of increasing efficiency has a great impact and the results have shown that it will soon be implemented all over the world.

1.9 Collaborations & Partnerships:

For the manufacturing of vertical axis wind turbines, we found different collaborations. The collaborations were based on the manufacturing and commercialization of the turbine.

First, we reached Fauji Fertilizers for installing the turbines in their wind farms situated in Sindh. Apart, we approached different independent startups for robust manufacturing of our turbine. Zambeel Machine Craft is one of those startups which helped us with the 3-D printing of the testing blades. The blades we used initially for the testing were made of a PLA material and were tested in the wind tunnel for accurate length, angle, and airfoil type measurement. The similitude we got from the analysis and the testing of these blades helped us in the procurement of the real blades.

For commercialization, we are also in talks with the National Highway Authority (NHA) to install the turbines in the motorway tunnels. The conversation went smooth, and the partial agreement was done to install the turbine on a Gilgit side. Motorway tunnels in the northern areas of Pakistan usually have power issues and are not curtailed with the improved material. So, installing the turbines in those high-speed areas could have solved the issue.

CHAPTER 2: LITERATURE REVIEW

To get a decent grip on the basics and then the detailed concepts revolving around the VAWT, we conducted a comprehensive literature review. This includes all the necessary parametric studies, studies for simulations, design, fabrication, and placement of the roadside model as well as design and placement of the starter motor as well as the slats. Calculations are shown in this section after engineering studies which are part of future prototype development.

2.1 Basic working and components involved:

The basic working and components involved are discussed by Tore Wizelius [1]. Vertical axis wind turbines are relatively simple when it comes to the components involved. Rotor here is the major component which consists of constant cross-section blades. As the wind blows through the blades of a Darrieus VAWT, the blades turn due to lift and produce torque. This torque turns the generator and hence produces electric power. The blades of a VAWT are designed after considering all the aerodynamics to achieve the best possible results. By keeping all the manufacturing processes in consideration, good aerodynamic results can be obtained from the blades.

2.2 Computational modeling

There are different computational techniques to accurately predict the performance and efficiency of a vertical axis wind turbine [2]. The three main approaches to modeling the VAWT include:

- Momentum models
- Vortex models
- CFD Models

Each of these approaches has its own merits and demerits. The basic idea behind these is to find the relative velocity and as a result the tangential force component of the individual blades at azimuthal locations. Our major focus has been on the CFD Models.

1.7.2 Momentum models (Blade Element Momentum Theory):

This theory is used to determine the performance of a wind turbine based on its mechanical and geometric parameters as well as the characteristics of the interacting flow. Local forces on the turbine blade are calculated using this theory. In this theory, angular momentum is included in the model which implies that the wake has angular momentum. This means that immediately after interaction with the rotor, air rotation is initiated, and the wake regions are produced. Angular momentum must be considered since the rotor is rotating because of its interaction with the wind.

1.7.3 Vortex models:

There is another type of model named a simplified free vortex wake model (FVW) which provides another approach for modeling and testing the vertical axis wind turbine. It is also termed the vortex sheet and ring wake model (VSRW. The model was developed to test the turbine under steady conditions initially and to calculate the aerodynamic performance of a vertical axis wind turbine. This model consists of:

- Vortex Sheets
- Vortex Rings

The vortex ring is obtained by the equations of the motion on the control point. By this method, we first determine the analytical formulae to reduce the computational time. It is also used to determine the wake flow regions in the model. The results are compared with the experimented results. The normal and tangential force coefficients obtained from the three models are in coordination with each other and with the measurement results at the low wind speed. The coefficients we calculated from the above methods are then used to measure the values such as torque, power, and tangential forces on the turbine.

1.7.4 Computational Fluid Dynamics Model:

We used the computational dynamics approach to evaluate the performance of our model. The CFD approach is flexible and thus helpful in analyzing the unsteady aerodynamics involved in the modeling of wind turbines. CFD is very accurate when it comes to predicting the performance of wind turbines having variations in terms of different tip speed ratios and high or low solidity. Although the CFD approach is computationally expensive, however, it is much more accurate when it comes to predicting the performance of wind turbine models.

2.3 VAWT Performance

The performance parameters that play a key role in turbine working and performance are discussed in detail with their effects on the overall efficiency by Parascivoiu [3]. He also talks about the double multiple streams tube model. Some are discussed below:

2.3.1 Tip speed ratio:

According to research, we realized that several wind turbines have a cut-in speed of around 3-4 m/s. This means that they start working at this wind speed. Before designing the turbine, one of the crucial steps is to determine the operational wind speed of the turbine and its tip speed ratio.

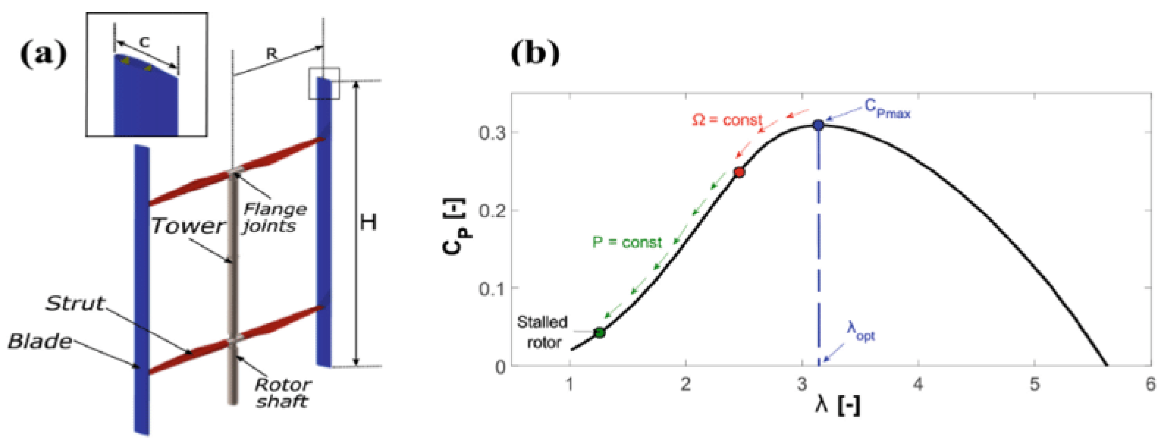


Figure 14: TSR Variance with Cp

These calculations help in determining the turbine's size. After determining the operational wind speed for the turbine, the next step is to set a particular tip speed ratio for the turbine. The tip speed ratio is given by

$$\lambda = wr/V$$

Where ‘wr’ is the rotational velocity of the wind turbine and ‘V’ is the freestream wind velocity.

2.3.2 Geometry Definition:
After the T.S.R has been selected, the VAWT geometry can be defined through the ‘solidity’ which is a dimensionless parameter.

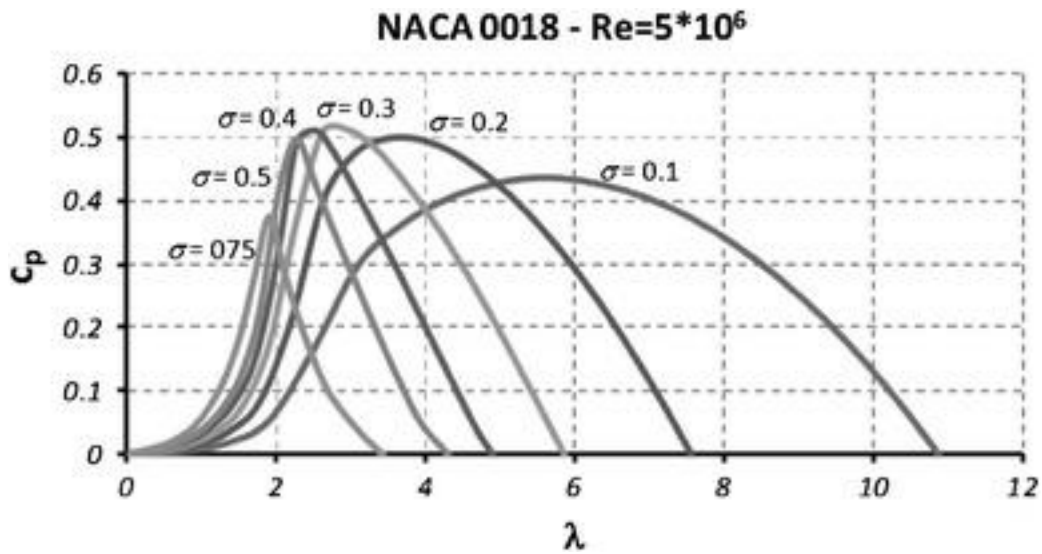


Figure 15: Solidity variation with design parameters

Solidity is given by:

$$\sigma = Nc/d$$

Where,

σ = Solidity

N = no. of blades

c = chord length of blades

d = diameter of the rotor

2.3.3 Performance prediction:
After defining the T.S.R and the solidity of the turbine, next the actual VAWT performance was to be predicted. For this, we needed the forces that are acting on the blades using:

- The relative wind component ‘W’
- the angle of attack ‘α’

During the rotation of the blade, the angle of attack continuously changes because of the relative velocity variation. The magnitude and orientation of the relative velocity are determined by V and wr. This affects both the drag and the lift forces on the blade. The magnitude of the resultant force acting on the blade changes as the lift and drag forces change. The resultant force is composed of a normal component and a tangential component. The tangential component produces the necessary torque for rotating the turbine and generating electricity.

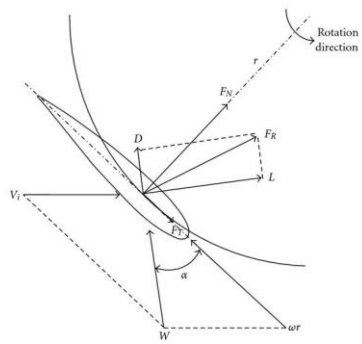


Figure 16: Airfoil angle of attack and relative wind speed

Average Torque:

The tangential force coefficient acting on the blade is given by:

$$C_t = C_l \sin\alpha - C_d \cos\alpha$$

Here, the angle of attack α is determined by the T.S.R, and the Lift and Drag forces are determined through CFD calculations.

The coefficient C_t is used to determine the tangential force component acting on the blade. F_t is given by:

$$F_T = 1/2\ C_t \rho c h\ W^2$$

h = height of the turbine

ρ = density of air

The F_t given above represents the tangential force on the blades only at one azimuthal location. To determine F_t at all locations, we take an integral. The average tangential forcing acting on the blades during rotation is given by:

$$F_{T\text{avg}} = \frac{1}{2\pi} \int_0^{2\pi} F_T(\theta)\, d\theta$$

Using the average tangential force, we can calculate the average torque acting on the blade using:

$$\tau = N F_{T\text{avg}} r$$

Power & Efficiency:
The power produced by a wind turbine is given by:

$$P_T = \tau\omega$$

The efficiency is given by the power ratio which the turbine extracts from the wind and the total available power in the wind as given by the following equation:

$$COP = P_T/P_W$$

$$\text{Where } P_W = 1/2\ \rho d h\, V_\infty^3$$

2.4 Manufacturing and assembling
Manufacturing methods were discussed in detail [4] about how we went about manufacturing our prototype model. Different machining operations applied while making the complete VAWT assembly were studied in detail. They are described in the methodology section.

The major prototype design considerations included bearing and airfoil designs, turbine height, chord length, cut-in speed, power and torque required, etc. We chose bearing 6203 for our design. We concluded in our research that the optimum airfoil selected is the NACA 0018. The data points in our research based simulations are given in Appendix 3: Simulation Data.

2.5 Aspect Ratio

The aspect ratio is the height of the turbine divided by the rotor radius. The implications of choosing a certain aspect ratio were studied [5] and discussed among the group members, faculty advisors, engineers, and working professionals to conclude the required aspect ratio for our turbine.

2.6 Design Parameters

The effects of the design parameters on turbine performance are also discussed in detail [6]. Parameters such as the number of blades, chord length, blade length, Reynold’s number, solidity, TSR, etc. were considered both in calculations and simulations to come to an optimum design for our turbine. It was concluded that the efficiency obtained while moving from 2 to 3 blades is substantially higher than that achieved from 3 to 4 blades, so we decided to go with the 3 blades design to get a better cost.

As the number of blades increases, the turbine achieves a cylinder model offering more tension losses in the model. According to research on VAWT, 3 blade design is the most efficient.

2.7 Possible Configurations

The various possible configurations for our design including Savonius, Darrieus, hybrid, Giromill, straight bladed, egg-shaped, etc., were reviewed in detail [7] and a conclusion configuration of H Darrieus was reached due to its relatively simpler design and better efficiency than the inferior designs.

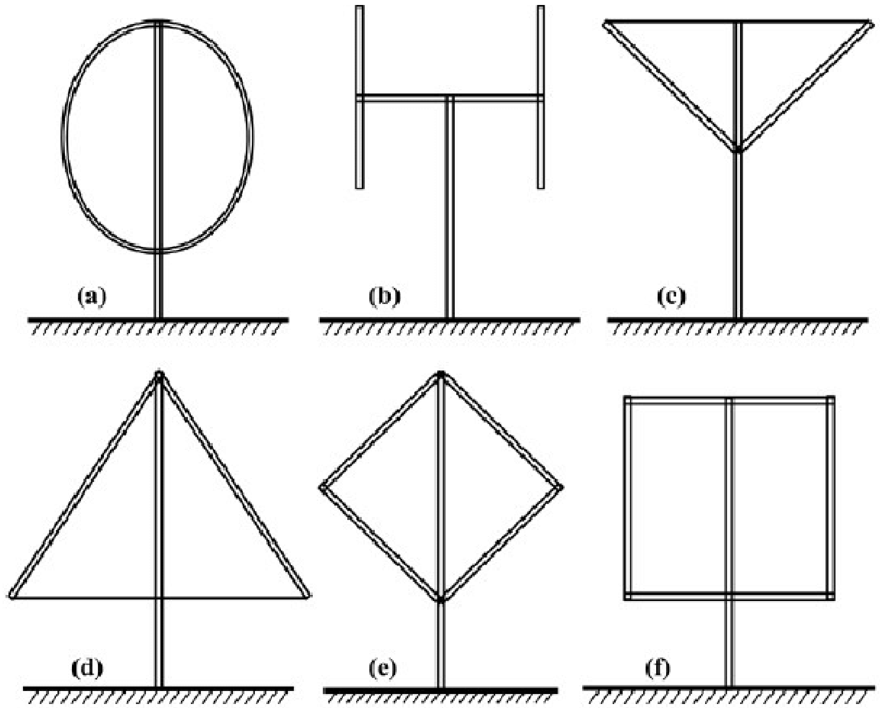


Figure 17: Possible Turbine Configuration for Darrieus Model

2.8 Scale Selection

The feasibility of making a small-scale turbine was also reviewed [8]. The results from the paper discussed favor a 3-blade rotor turbine.

2.9 Pitch Angle

The effects of higher pitch angle [9] on the rotor performance are also studied. Having the availability of a variable pitch is a huge plus point to adjust to the direction of the wind and have greater efficiency. However, due to the design configuration of a VAWT and design complexities, a varying pitch model is not achievable at the bachelor's level.

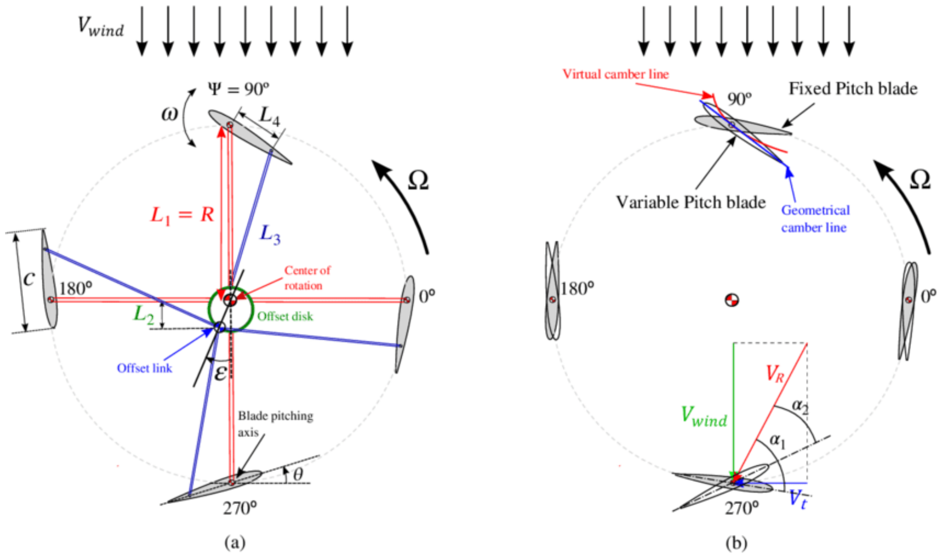


Figure 18: VAWT Pitch Angle Variation

2.10 Self Starting

The difficulties involved in the self-starting of the VAWT rotor [10] have also been discussed in detail. It is difficult to get a Darrieus turbine to rotate itself due to the higher initial torque required than is available. However, a hybrid Savonius-Darrieus model might offer a solution. This, although is a much more complex design we decided to move towards a starter motor design model which will get the initial push from a power source.

2.11 Unsteady Winds

The effects of unsteady wind gusts were also studied [11] on the VAWT. The research concludes that unsteady wind gusts affect the turbine performance and efficiency.

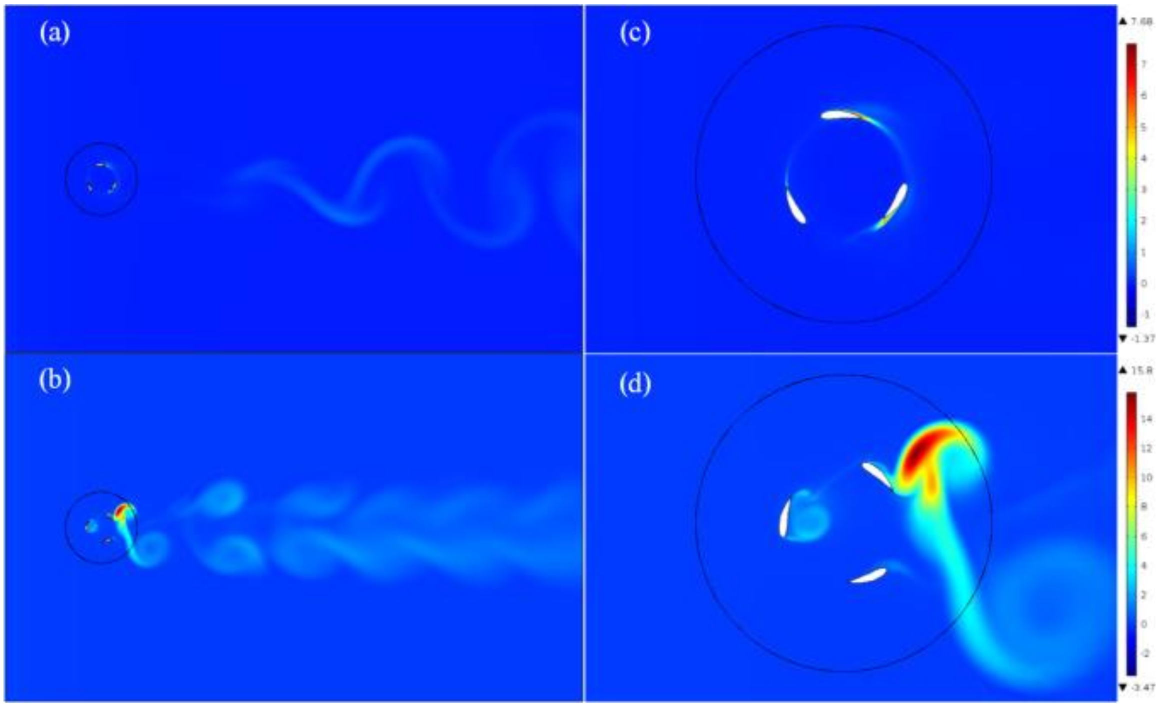


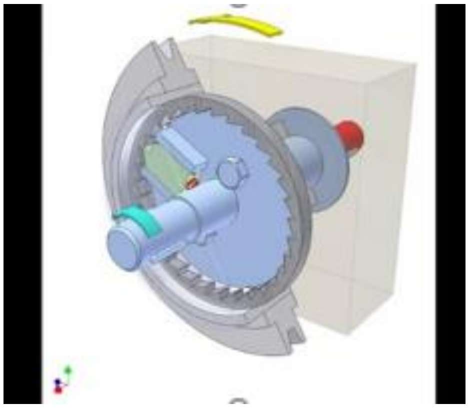
Figure 19: Unsteady Wind effects on Simulation Results

2.12 Starting Torque:

We all know that the vertical axis wind turbine needs starting torque for the operation. The theory behind it is that the weight of the turbine is large enough to not support the starting of the turbine by just the wind speed. So, for the starting torque, different methods are being used in the world.

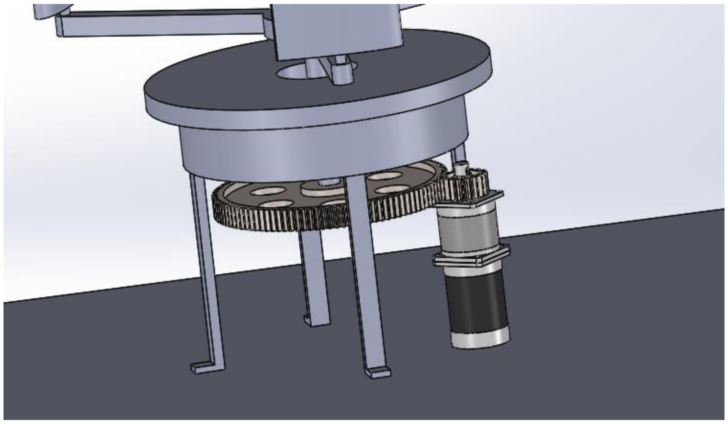
Though the brainstorming on starting torque led us to find different ways of providing the starting torque with few of them are explained here:

2.12.1 Clutch-Ratchet Mechanism:



The mechanism was devised to power the turbine from the motor initially and then disengage it from the main assembly. After being disengaged, the main assembly gets connected with the generator and starts extracting the power normally. This setup, however, involved a complex engineering setup with not a cost-effective method for the starting torque.

2.12.2 Generator Assembly:



Another mechanism that we devised was to use the same device that will act as a motor during the start and takes the power from the secondary battery. After that, the same device will act as the generator to extract the power out of the turbine. This method, however, did not look feasible on practical grounds.

2.12.3 Control Circuit based system:

The best mechanism we have devised so far is to program the whole system. Using a Tachometer and Anemometer, the system will measure the speed of the wind and when it goes below a certain threshold, it will power the system for starting torque. In this way, a fully automated turbine system would be generated. The base will be mounted with the motor with the system connected to Arduino. After it gets the starting torque, the motor sets free with the generator mechanism coming into the role here.

Code:

```
#include <Stepper.h>
const int stepsPerRevolution = 200;
int b = 0;
Stepper myStepper(stepsPerRevolution, 8, 9, 10, 11);
void setup() {
  mySteppper.setSpeed(150);
  Serial.begin(9600);
  pinMode(12, OUTPUT);
  pinMode(13, OUTPUT);
}
void loop() {
  int a = analogRead(A0);
  Serial.println(a);
 if(a > 180) {
  digitalWrite(12, HIGH);
  digitalWrite(13, HIGH);
  myStepper.step(stepsPerRevolution);
   myStepper.step(stepsPerRevolution);
    myStepper.step(stepsPerRevolution);
     myStepper.step(stepsPerRevolution);
```

```
      myStepper.step(stepsPerRevolution);
       myStepper.step(stepsPerRevolution);
        myStepper.step(stepsPerRevolution);
         myStepper.step(stepsPerRevolution);
         b = 1;
  }

  else {
    digitalWrite(12, LOW);
    digitalWrite(13, LOW);
    digitalWrite(8, LOW);
    digitalWrite(9, LOW);
    digitalWrite(10, LOW);
    digitalWrite(11, LOW);
  }

  if (b == 1) {
    delay(1800000);
    b = 0;
  }
}
```

This code was implemented for the starting torque.

2.13 Slats

The design, positioning, effect, and feasibility of slats on the leading edge of the rotor blade [12] were also studied. The optimum angle for slatted wake separation was studied and adjustable slats possibility was also under evaluation. We reached upon an optimum adjustable slats design to test the design feasibility and an ideal angle of 45 degrees for the slats

All the literature review done for our turbine studies proved to be very helpful and aided us in the selection of an optimum model with maximized efficiency.

Chapter 3: METHODOLOGY

As we started with the motivation of commercializing the project; and contributing to the goal of achieving a sustainable environment in Pakistan. This motivation led us to think beyond the box and develop something that had not been implemented. Proper chronological order for our project was devised right from the start of the year.

This section consists of the methodology employed to manufacture our design and the process we followed in chronological order.

3.1 Project Plan

Following is the project plan explained in the form of steps that were followed during the several steps followed for finalizing a design:

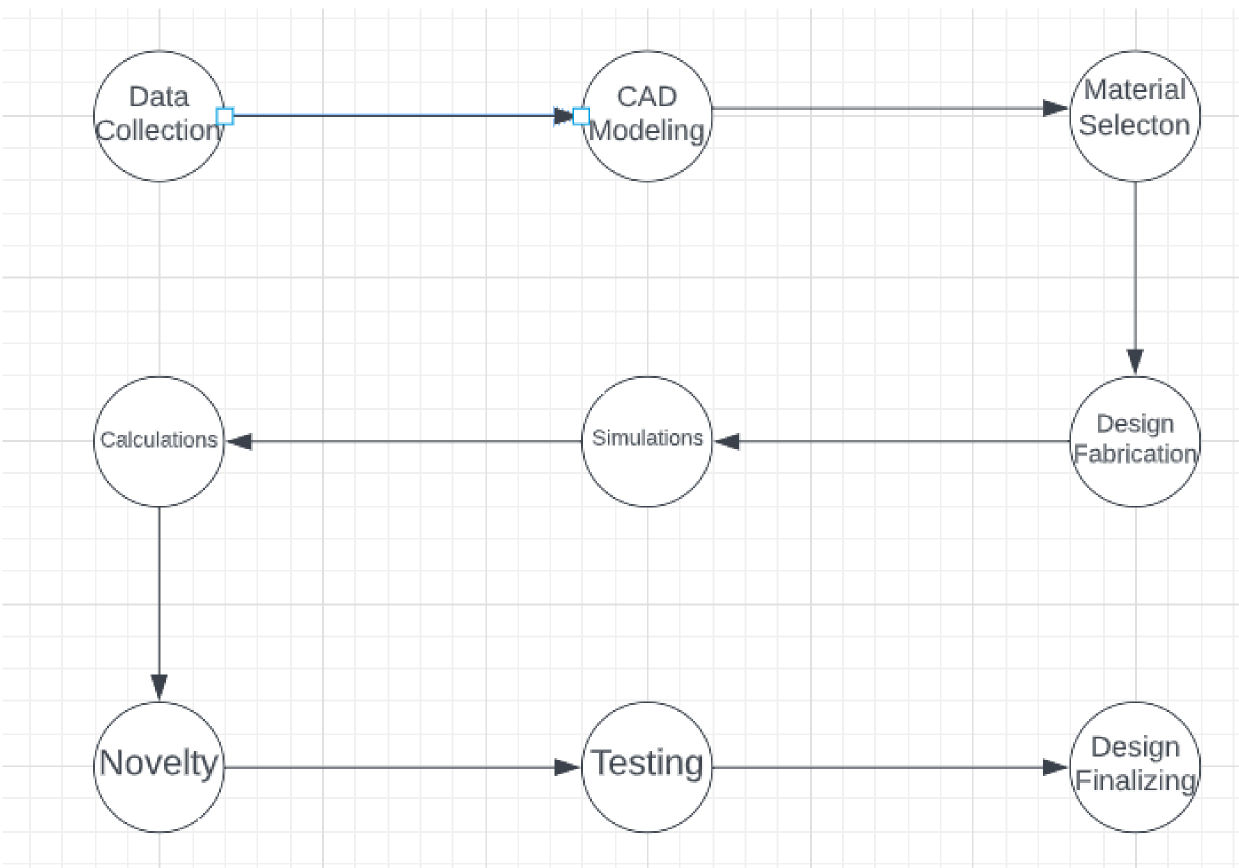


Figure 21: Process Flow for our Project

3.2 Site Potential Data Collection

3.2.1 Wind Data:

We did some additional research, collected the wind data from various sources, and got to know about the average wind speeds here. The central region of Pakistan lacked the wind potential we wanted. These areas mainly have an average speed of 2 to 5 ms^{-1}. This speed is not enough to pass the threshold of the vertical axis wind turbine. Meanwhile, the data we collected [13] from the other cities are as follows:

CITY	**AVERAGE WIND SPEED** $\boldsymbol{ms^{-1}}$
Islamabad	2.59
Karachi	6.2
Lahore	3.79
Gawadar	5.81

However, the wind data we collected was the source of secondary importance as it revealed that it may not drive the turbine in normal condition and additional wind gust (which we provided from moving cars in our project) is required.

3.2.2 Environment/ Climatic Conditions in the region:

Environmental conditions were kept into consideration while designing a turbine. Be it in stormy conditions or hot arable land, the design should sustain every condition. For that purpose, we studied the composites' properties that we were using in our project. It included turbine blades, shaft, connecting rods, bearings, batteries, etc.

The data revealed that Aluminum is lightweight and can sustain extreme climatic conditions as well. We, therefore, used Aluminum 6063 T6 as the major material in our project. It is an alloy of Aluminum with small quantities of magnesium and silicon [14]. It also heat-treated and weldable. The properties of Aluminum we found are shown here:

PROPERTY	VALUE
Melting Point	655 °C
Density	2.70 g/cm³
Thermal Expansion	23.5 x10^-6 /K
Modulus of Elasticity	69.5 GPa
Thermal Conductivity	201 W/m.K
Electrical Resistivity	0.033 x10^-6 Ω .m

3.2.3 Real-time Data for Original Sight:

Tests were conducted on different sites and the data was collected based on those tests. The wind tests were done on different chowks of Islamabad. The bustling traffic gave the result as we expected. Apart from that, we took help from online sources to collect the data from different areas in Pakistan.

Normal Wind Speed = $6ms^{-1}$

Location	**Vehicle Type**	**Vehicle Speed** ms^{-1}	**Ground Distance ft**	**Car - Anemometer Distance ft**	**Anemometer Reading** ms^{-1}
NUST	SUV	60	4	1.5	3
NUST	Bike	50	4	1	2.5
Kashmir Highway	LTV	40-50	4	2	6.5
Kashmir Highway	HTV	30-40	4	2	5.5

3.2 CAD Modelling:

After we considered all the factors to optimize the design, the next step was to model it. SolidWorks was used for that purpose.

For design optimization, we used two techniques:

- Actual Data based MVP testing
- Simulations/ CAD optimization

The values were selected based on the results of these two tests to finalize the design.

The designing phase includes the designing of:

- Blades
- Shaft
- Bearing
- Connecting Rods
- Hub
- Base
- Iron Plate
- Slats

The initial design we made consisted of the similitude of the main product. The plan was to conduct all the testing on the cost-effective minimum viable product and change the parameters after the optimized results.

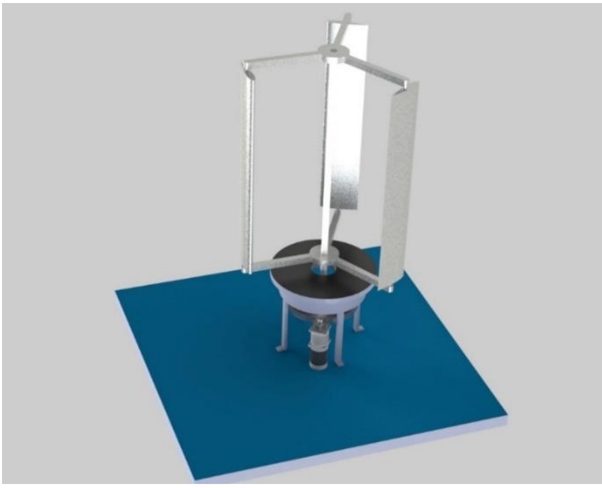


Figure 22: Final Design CAD Model

3.3 Material Selection

3.3.1 Analysis

The materials that are used for VAWT in common are those of high resistance to failure as well as being lightweight. This combination is hard to find as an increase in one mostly results in a decrease in the other or the quality of material increases which means more cost. After careful analysis of material properties and already used materials for such turbines, we concluded to use Aluminum 6063 T6 was used for our main body including shaft, blades, connecting rods, hub, and bearing. The base plate between the generator and the rest of the assembly is made from iron and so is the ground base.

Figure 23: Slats integrated with turbine blade

We chose balsa wood for slats manufacturing as it is easy to come by and manufacture. Balsa wood also lends us satisfactory results at an optimum angle for slats. However, if we use a smoother profile for slats, even better results can be achieved.

3.3.2 Procurement

The efficient logistics and supply chain network was kept in consideration to meet the timely material demands. Mostly, the material was procured from the College Road Rawalpindi. From bearings to shaft, nuts & bolts, and basic metallic parts we ransacked the whole area to find the best vendors.

However, materials like the metallic base stand and the wooden base were tested using FEA analysis via rigorous finite element testing to make sure that the material can withstand the stresses being generated by the turbine. After finalizing, we had the metallic base and stand made through machining processes including welding, lathe, sheet metal, etc.

We have used wooden material for the slats because it was easily procured. The filing of the wooden piece made the airfoil design for the slats. Wood is a low-weight material that helped us largely in the testing phase. The results could have been better with other smoother materials like Aluminum but because of the manufacturing limitations, we used woods for the final design.

3.4 Design fabrication:

3.4.1 Manufacturing Aid

There were different manufacturing processes that we utilized for the fabrication of the turbine. Usually, VAWTs in Pakistan is being manufactured in the existing setups of HAWTs. As vertical turbines are not yet common, very little help from the industry was taken, and we procured the complex manufacturing materials.

For blades, the most complex ones, we had a choice of manufacturing a mold, and then with a process of blow molding, blades could have been manufactured. Yet considering the price of making the mold first and then material and labor costs for this process would have skyrocketed the budget. So, we imported the blades of the NACA 0018 profile according to our requirements.

Other than that, we took major help from the manufacturing and resource center, NUST. It included the machining of fixtures and mating of parts.

The knowledge of manufacturing processes and advanced machining was used to give the tolerances to our mating parts. We also took our engineering drawing knowledge into consideration, and it helped us in the 2D drawings of our project.

In the end, we fixed the motor, and its assembling was done using wood as a major material in the structure because of being cost-effective. Final assembly was done on our own using the equipment in the RP lab.

3.4.2 Blades:

For our initial testing, we 3D printed the blades with the blade profile NACA-0018. We printed three profiles and made the blades of approximately 40 cm in height.

3.4.3 Shaft:

For finalizing the shaft, we studied the properties of different materials to optimize the results of our experimentation. After thorough research, we selected the Aluminum shaft because of its lightweight and the ability to resist the axial stresses caused by aberrations. The shaft diameter we chose for our MVP was 18mm (1.8cm) and a length of approximately 60 cm at the bearing end.

3.4.4 Bearing:

After considering our requirements, we selected the bearing using the NSK catalog. The additional factors we considered while choosing the bearing were:

1. Stresses
2. Power Transmission

6203 was fulfilling all the parameters and was selected on that basis.

3.4.5 Connecting Rods:

Rods that couple blades with the shaft are termed connecting rods. Connecting rods consist of the set of couplers as well as the rods. Rod diameter we used for the connection was approximately 8mm with the threading on it for the bolted connection with the blades.

3.4.6 Hub

The hub is an important part of the design assembly which is a connecting point between the main shaft and connecting rods and hence, the blades. The hub was manufactured by procuring an aluminum piece of required dimensions from the market and then applying machining operations through a lathe machine on it to produce an inner hole slightly larger in diameter than the shaft.

3.4.7 Base

The base plate is a disc made of iron. It is a base for holding the shaft as well as connecting it to the generator through gears. An iron disc was managed from Saddar, and we did a lathe in the center to accommodate bearing having an inner diameter equal to that of the shaft. The bearing was press-fit inside the base plate while the shaft was press-fit inside the bearing.

On the lower side, the shaft was integrated with a gear set that connected to the generator assembly. Welding operations were done to connect the base plate with the generator and iron square base through an iron stand to provide a strong, sturdy, and stable base.

3.4.8 Iron Stand

Iron base is used in the fundamental area on which the whole assembly is standing. It has levelling screws at the bottom to achieve the perfect level for our turbine.

3.4.9 Slats

Slats are the major portion of our project and are used to increase the overall efficiency of the turbine using wake separation delay. Balsa wood piece in length was procured and slat manufacturing was done using wood profiling.

3.4.10 Minimum Viable Product Fabrication:

MVP was fabricated and made ready for wind tunnel testing. The parts we manufactured above were then assembled. We didn't include the generator first to collect the data in the no-load condition so that we can calculate the turbine brake torque and brake power, and then we tested out turbine by coupling the generator with DAQ to find the electrical power density.

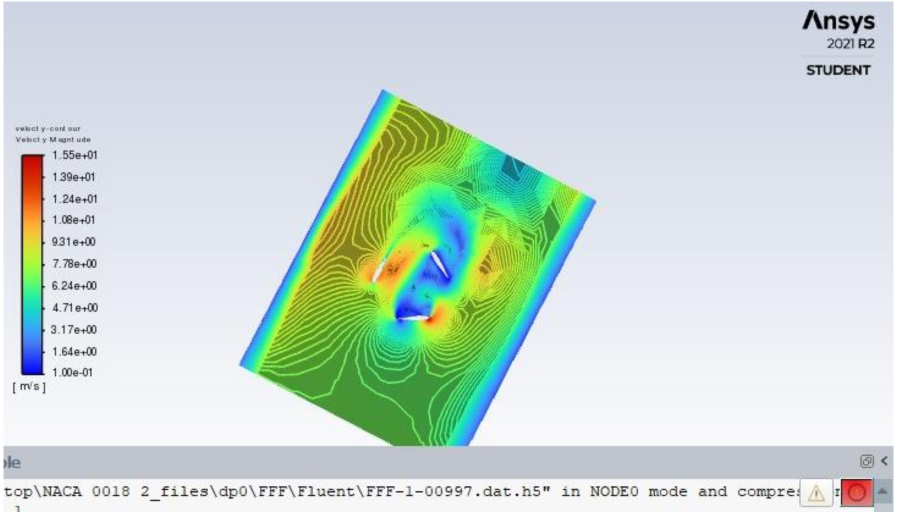
3.5 Simulations:

Simulations were done on ANSYS-Fluent software. The order we followed for the simulation was:

- Airfoil face 2-D Simulation
- Dynamic Meshing 2-D Simulation
- 3-D Simulation of Blade
- Dynamic Meshing 3-D Simulation
- Total Simulation of VAWT
- Simulations with Slats

3.5.1 Airfoil face 2-D Simulation

The first simulation was done using the triangular meshing and increasing the nodal points at the contact surface to generate smooth results. The velocity and pressure contours are shown respectively:



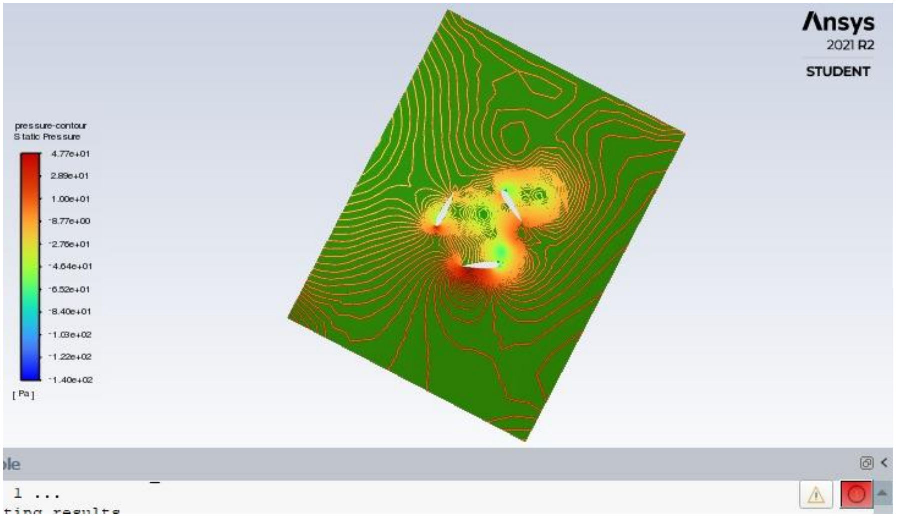


Figure 24: Simulation in 2D

3.6 Mathematical Calculations:

For the mathematical calculations, we performed comprehensive research and collected useful data. The data we collected included the wind speed across different areas in Pakistan and calculations were done based on that data.

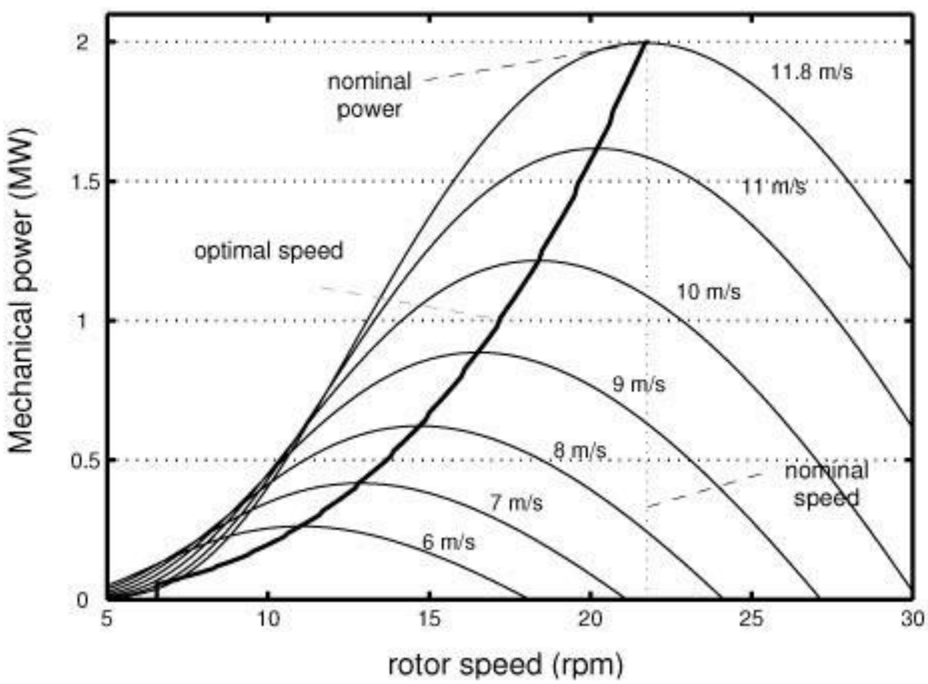


Figure 24: Mechanical Power Variation with Rotor Speed

First, we calculated the wind power present in the air as follows:

$$P_{wind} = \frac{1}{2}\rho A V^3$$

Here,

$\rho = Density\ of\ Air$ = 1.225 kgm^{-3}

A = Swept Area

V = Wind Available Velocity

We have,

$$A = \pi RL = \pi * 0.29 * 0.2 = 0.1822 m^2$$

Here the swept area has been calculated using the radius and height of the turbine we have designed.

Now, the average wind speed we have calculated using the intuitive analysis and the data collected from the wind websites of Pakistan is:

$$\text{Velocity} = 6\ ms^{-1}$$

Note that the speed includes the wind gust generated by the moving cars on the road. The data was collected on a Kashmir highway on a normal windy day using an anemometer.

Using the above data, we can calculate the available wind power as:

$$\boldsymbol{P_{wind} = 24\ Watts}$$

We know that all the energy present in the wind is not being utilized by the turbine and it initiates the loss right from the process where the wind interacts with the blade. This factor of wind power being utilized by the turbine is defined by the Betz's limit where the graph shows different efficiency percentages for different parameters as follows:

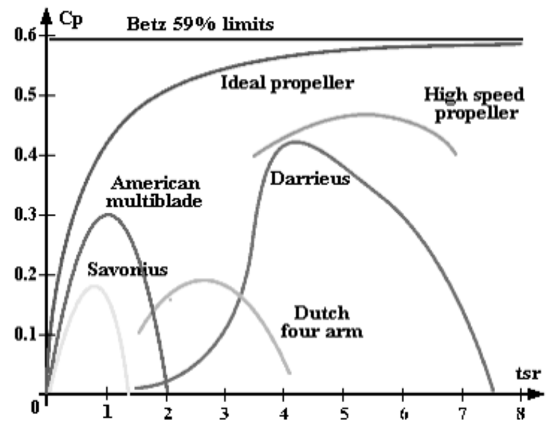


Figure 25: Cp Variation with TSR

The graph shows that for calculating the Betz limit, we need to calculate the tip speed ratio first.

$$\text{TSR} = \frac{Speed\ of\ the\ blade\ at\ its\ tip}{\text{speed of the wind.}}$$

$$= \frac{33}{6} = 5.5$$

From the above graph, it shows that for the Darrieus turbine, the c_p value is approximately = 0.35

Now calculate the available mechanical power as:

$$\boldsymbol{P_{mech} = C_p * P_{wind}} = \textbf{8.43 Watts}$$

Now that we have catered to the mechanical losses. The turbine is rotated, and the power is transmitted to the base. At base we have the generator installed and the electrical losses are experienced here.

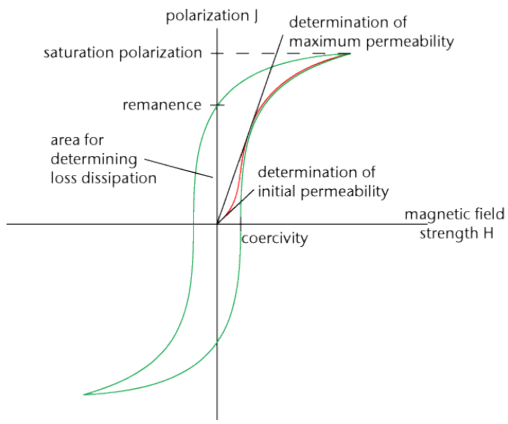


Figure 26: Hysteresis loop for electrical losses

These losses are due to the reasons as follows:

- Electrical or Copper losses
- Core losses or Iron losses
- Brush losses
- Stray load losses.
- Wire Resistances

The study has shown that these losses can account for nearly 60 percent of the losses of the power and it can result in a huge storage loss of the power.

The available power after this step can be calculated as:

$$\boldsymbol{P_{available} = 0.4 * P_{mech}} = \textbf{3.3 Watts}$$

So, it means that an approximation of 15 watts can be obtained out of the single turbine we are using. The combination of 2 such turbines can ensure 30 watts of power generation and fits in the business model proposition we have discussed earlier. Furthermore, the promising results are shown by the induction of slats in these turbines also increases the power by increasing the rpm.

As we know,

Power = Torque * RPM

The addition of slats increases the overall weight of the turbine. It means that it increases its torque due to weight addition, furthermore the adjustment of the angles of the slats ensured the maximum drag and we have seen in the experimented results that the torque increased nearly 3 times to what it was initially.

On the other hand, the slats addition decreased the rpm due to the increase in the torque as mentioned above. However, the power calculation showed that the factor of increase in the torque is much greater than the decrease in the rpm and overall power was increased.

The concept can be widely applied to the larger turbines and the same way a 100 watts turbine can extract 120-125 watts of Power due to this concept.

3.6.1 Additional Calculations:

Apart from the power-based calculations, we did some other calculations to properly design the turbine. The details of all these calculations are shown below:

- The rotational speed (ω) of the wind turbine was tested in different conditions and based on experimental results, the rotational speed we got at normal atmospheric conditions was 90-150 rpm.

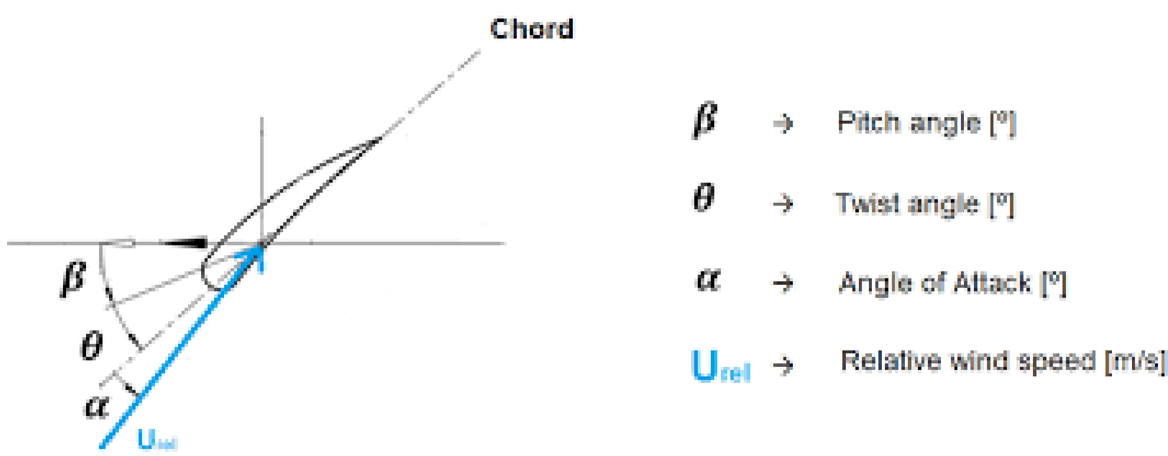


Figure 27: Additional Parameters

- Pitch angle is the angle between the direction of the wind to the lateral axis of the turbine. It varies depending upon the direction of the wind but upon calculations, it came out to be 5-7° in our case.

- The blade twist here depicts the changing chord line from the blade root to the tip. Twist Angle here is the property of the blade and the profile you are choosing for it. Typically, the twist is around 0-20° from root to tip which is the angle at which the wind strikes the blade from the chord length or the tangent to the leading edge of the blade.

- The angle of attack is the relative angle at which the wind meets the aerofoil. This is the angle between the chord length of the blade to the direction of wind trajectory. Normally, the angle of attack in a vertical axis wind turbine is 10-15° to generate the maximum lift.

- The solidity of the turbine is the ratio of the overall blade area to the swept area of the vertical axis wind turbine.

In our case, it was:

$$\sigma = \frac{nc}{d}$$

Where 'n' is the number of blades, 'c' is the blade chord length, and "d" is the diameter of the turbine.

The calculated solidity in our case is = $\frac{3(5)}{50}$ = 0.3

- Other factors were also calculated based on Q-blade software including the coefficients of the turbine. All these results are shown below:

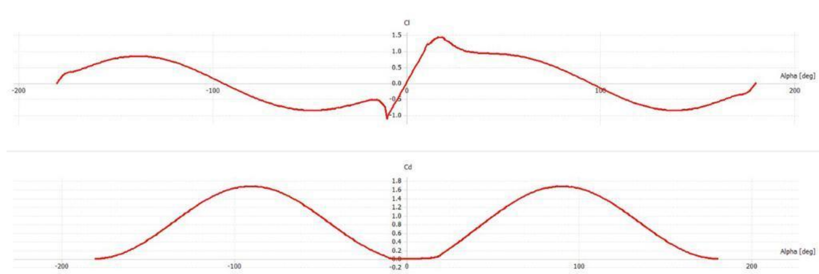


Figure 28: VAWT coefficients Variation on Qblade

These results show the lift and drag coefficient based on different turbine positions

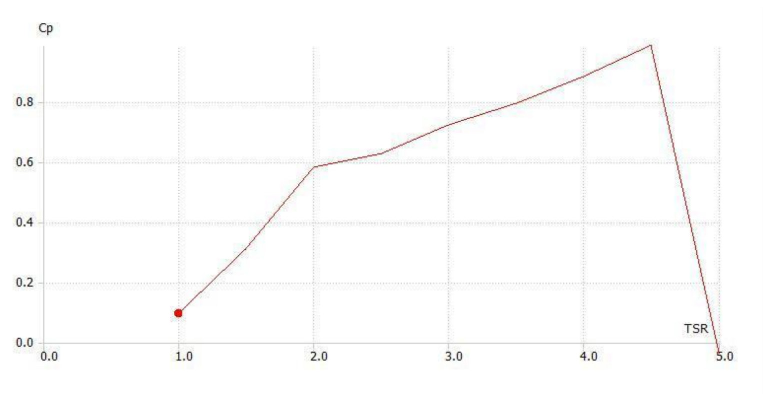


Figure 29: Cp variation with TSR on Qblade

This graph shows the power coefficient against the TSR value which we calculated above.

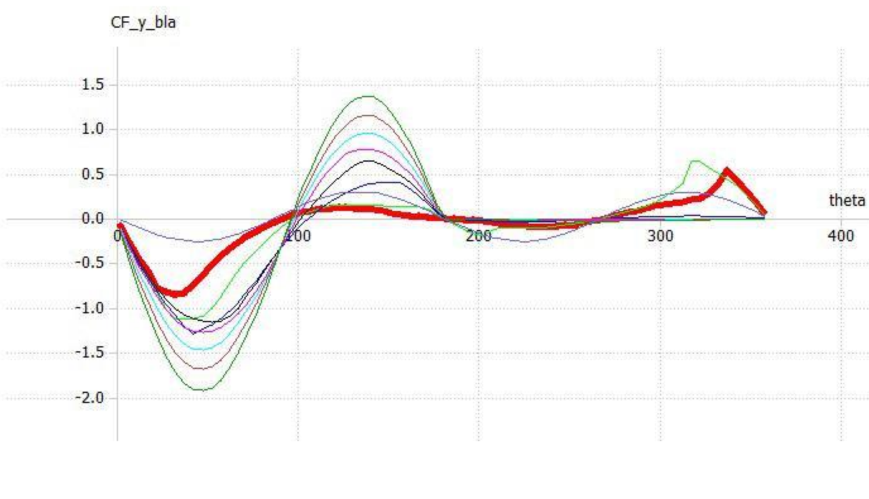


Figure 30: Cf variation with theta

This coefficient shows the force values to determine the torque on the turbine.

3.7 Novelty

3.7.1 Slats Introduction in the Assembly

Balsa wood slats were introduced in our turbine after profile adjustment. The slats are adjustable on the blades. They were adjusted at different angles ranging from 9 degrees to 45 degrees to achieve the maximum possible efficiency.

At different slat angles, the drag component increases and there are different values for torque and RPM. An optimum angle with maximum possible simultaneous values of both torque and rpm is to be found.

3.8 Testing

Turbine testing was done after design fabrication without slats on different conditions that include:

- Testing without slats
- Testing with slats

3.8.1 Testing without slats

Testing was done using the fan provided in the RP lab at $5ms^{-1}$ to check our design feasibility and values. Our purpose was to measure RPM and torque for different conditions and provide the proof of concept for improvement after the introduction of slats.

3.8.1.1 RPM

To check RPM, the turbine was rotated freely under the fan wind and RPM was measured using a tachometer.

3.8.1.2 Torque

To check torque, a mechanism was introduced consisting of a pulley and weights. The shaft was tied using a thread that passed over the pulley and weights were added to the lower end. Rotation was allowed with the addition of weights gradually until the turbine ceased its motion. At that point, the weight equaled the torque provided by the turbine to the generator.

3.8.1.3 Brake Power

The difference in height of the weights from the starting time to the ending time was used to calculate the change in the potential energy of the turbine which then provided us with the brake power of the turbine.

3.8.2 Testing with Slats

To provide proof of concept and our deliverable of novelty with increased efficiency, we did testing with the introduction of slats as well. Adjustable slats were attached with the blades and testing was done at different slat angles for:

- RPM
- Torque
- Brake Power

The methods used for measurements were the same as already described in the above section without slats. Just that we tested slats at different angles.

3.8.3 DAQ

DAQ (Data Acquisition) is used to sample signals that can calculate real-world physical phenomena and converting them in digital form to be used by computer as well as software. It is used to measure electrical or physical phenomenon like voltage, current, temperature, etc.

Figure 30: DAQ Coupled with the Generator

We used DAQ in the testing phase of our FYP. We combined DAQ with LabVIEW in our computer and coupled it with the generator of VAWT. The circuit provided us with the values of voltage and power density via an AC voltage graph.

3.9 Finalizing the Design

A finalized design was selected after detailed testing and analysis. All the effort made in previous stages of modeling, simulations, assembling, and testing bears fruit in this stage when a final design decision is made for our VAWT model. This model has an aspect of novelty and has better efficiency as will be discussed in the next stages of results and conclusions.

Figure 31: testing with slats at different angles

Figure 32: torque (left) and RPM (right) testing

CHAPTER 4: RESULTS

We have successfully achieved the deliverables of our project. The turbine model prototype fabrication without an actual generator is done for a "controlled" experimentation phase to be held. We planned to test the turbine first under the no-load condition with minimum wind speeds of 6 m/s to assess the workability and efficiency of our design. We have run CFD simulations on our airfoil design in 2D to better assess the wind conditions that our turbine is going to face during its running. We have conducted experimental research to determine the feasibility of our project in the urban region. Different aspects covered so far are as follows:

4.1.1 Data Analysis:

We acquired an anemometer from RISE lab SMME to perform testing on the wind conditions in Islamabad. Several locations were chosen for this data collection. As our turbine is designed to be operated on the roadside, we did data collection on Srinagar Highway on windy data and in heavy traffic.

The results were better than we expected, and we were able to achieve an average wind speed of 6 m/s which is higher than the cut-in speed required for the operation of a wind turbine. Using this wind speed, we should be able to generate electricity that will be enough to operate the streetlights at the least. Now to imitate this wind speed that we require, all we need to do is provide ourselves with a controlled environment for experimentation.

Figure 33: Realtime Data Collection

4.1.2 CFD Simulations- Ansys:

The 2D simulations have given the promising results. The wind travel and vortex generation around our wing design are feasible for the appropriate lift generation for the running of our turbine under low torque and minimum wind speed. We are determined to run further simulations on our design to support our experimentation on a test basis. We conducted dynamic meshing in 2D, 3D blade simulation, dynamic 3D meshing for the testing phase. Some simulations of the final model are added in Appendix 2: Simulations.

4.1.3 Q-Blade simulations:

The Q-Blade simulations that we run on our blade profile NACA 0018 helped determine the wind characteristics around our turbine blades. The physical properties such as power coefficient, lift coefficient, and drag coefficient were determined to perform theoretical calculations on the given values. During our experimental run of the turbine and CFD simulations, we are going to compare these theoretical values with our experimental results to confirm that they both agree with each other which will reinforce the ingenuity of our project.

4.1.4 Fabrication:

We were able to fabricate the initial prototype design of our CAD model using the equipment provided by our school and the expertise of the MRC.

Initially, we did not integrate generator with our model as advised by the faculty supervisor. We tested our turbine under the no-load condition first. We then added the generator and coupled it with DAQ to get values for voltage and electrical power density. The initial prototype was completed after some visits to RP-lab and MRC. Some drawings used are added in Appendix 4: Engineering Drawings. The parts needed for our turbine model were procured from the city Saddar Road in Rawalpindi. We managed an aluminum road and support structures from Saddar and bought the 6203 bearings online for our project. The catalogue for bearings is available in Appendix 1: Tables.

Figure 34: Final Fabricated Model

4.1.5 Simulating the Roadside conditions using Lab Fan

For our calculations under a controlled environment, we managed to simulate the roadside conditions using the testing fan provided to us in the RP lab. The testing was done under the no-load condition first to provide us with the proof of concept. After that, we added generator and coupled it with DAQ to get results under load. No-load Testing was done while keeping under consideration the following conditions:

- Testing without slats
- Testing with slats

Our parameters of consideration were:

- RPM
- Torque
- Brake Power

We did calculations first with slats and then without slats to provide us with results of an increase in the efficiency of the turbine. While using slats, we did our experiments at the following degree angles:

- 9°
- 16°
- 12°
- 45°

4.1.5.1 Testing Under Load:

After no-load conditions, we used DAQ to get results with generator integrated with our model. We coupled DAQ with generator and connected it with LabVIEW in a laptop to get results for voltage and electrical power. The values that came out were as follows:

Voltage = 2 Volts

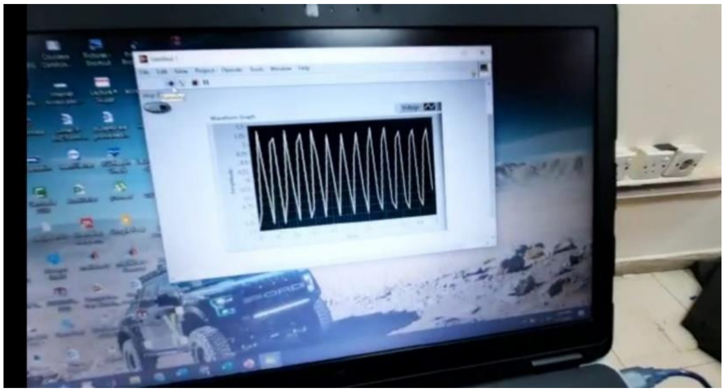


Figure 35: DAQ AC Voltage Output

All the results were tabulated, and the optimum angle was found. At different angles, torque and RPM differ which results in different values of brake power. We found after several test runs those **45 degrees** was the most optimized angle for our testing which provided us with a **44% increase** in the overall efficiency as shown in the table:

Sr.no	Slat angle (degrees)	RPM	Weight of load (g)	Moment arm (m)	Torque N/m	Brake (Watts)
1	Without slat	164	488	0.01	0.0478728	0.819135523
2	Without slat	170	485	0.01	0.0475785	0.843883995
3	Without slat	172	488	0.01	0.0478728	0.859093354
4	Without slat	158	493	0.01	0.0483633	0.797252879
5	9	88	538	0.01	0.0527778	0.484570574
6	9	92	543	0.01	0.0532683	0.511304656
7	9	87	548	0.01	0.0537588	0.487968628
8	9	88	538	0.01	0.0527778	0.484570574
9	12	104	579	0.01	0.0567999	0.616316782
10	12	105	574	0.01	0.0563094	0.616869477
11	12	104	580	0.01	0.056898	0.617381232
12	12	101	579	0.01	0.0567999	0.598538413
13	16	105	559	0.01	0.0548379	0.600749195
14	16	108	561	0.01	0.0550341	0.620124239
15	16	112	556	0.01	0.0545436	0.637360147
16	16	108	563	0.01	0.0552303	0.62233502
17	45	90	1684	0.01	0.1652004	1.551231756
18	45	92	1694	0.01	0.1661814	1.595119865
19	45	89	1684	0.01	0.1652004	1.533995848
20	45	88	1684	0.01	0.1652004	1.516759939

Discussions:

- According to the progress, we have a feasible minimum viable product that can produce enough power to light a small LED after some design optimizations.
- Theoretical calculations are compared with the experimental testing. This gives us proof of the correctness of our work.
- The simulations helped depict the wind behavior according to the environmental conditions in the twin cities and we can use these results to further help in conducting better simulations in three dimensions.
- Expense on our turbine model is reasonable and we expect a greater part of the expense to be from the tentative advancement of slats that we are planning to inculcate in our model.

- Fabrication of the prototype is done. Large scale fabrication will be conducted once the design is approved by the industry
- Proof of concept is depicted with the introduction of slats which gives us an increase in the overall efficiency of the turbine.
- With the novelty of slats at 45 degrees, we have introduced a concept of lift and drag-based hybrid turbine which will open new doors for research in VAWT.
- Our design is industrially scalable and appreciated by those in the industry. We expect to commercialize our project via connections with those working in this category of renewable energy.
- If applied across the country, it can start a new era of a renewable energy revolution in Pakistan and give motivation for other students to follow the trend and do more research.
- A research paper is going to be published depicting our success in efficiency enhancement due to the introduction of slats with the turbine blades resulting in delayed wake separation.

4.2 Cost Analysis:

So far so good, our project is running as cost-efficient as it could be. From what we have done until now, it is safe to say that we will be able to produce a cost-effective scalable turbine model that has a novelty to it preferably of pitch regulation using slats. The cost breakdown is provided as follows:

Sr No	**Item**	**Quantity**	**Cost**
1	Bearing	4	1400
2	Transportation	-	7700
3	Aluminum Shaft	2	730
4	Base Support	1	350

5	Generator	-	2700
6	Gears	3	700
7	Hardware	-	710
8	Sheets for base	2	900
9	Wooden Parts (Wood, Ply, etc.)	-	930
10	Base Plate	1	1070
11	Machining	-	2000
12	Miscellaneous	-	1380
13	Arduino	1	2200
14	Relay	2	250
15	H Bridge/ Motor Driver	1	400
16	Rectifier	1	400
17	Batteries	1	1000
18	Electrical Hardware		3000
		Total cost	**27,820**

CHAPTER 5: CONCLUSION & RECOMMENDATIONS

The project has met the deliverables required. The following conclusions can be drawn now:

- The idea of capturing wind energy from gusts shed by a fast-moving vehicle is feasible and applicable on fast-traffic highways of Pakistan.
- Ansys fluent CFD simulation is an efficient way to depict turbine behavior in actual circumstances.
- The turbine is expected to produce enough energy to produce profits for the project owners once the full-scale production is done.
- The blades made of aluminum are lightweight, strong, support tension, and thus are the ideal blades for our turbine design.
- The introduction of slats increases the overall efficiency of the turbine.
- In our case, at 45 degrees, we achieved an increase in overall torque and RPM giving us an efficiency increase of 44% which was very well to our theoretical calculations and even exceeded our expectations in some ways.

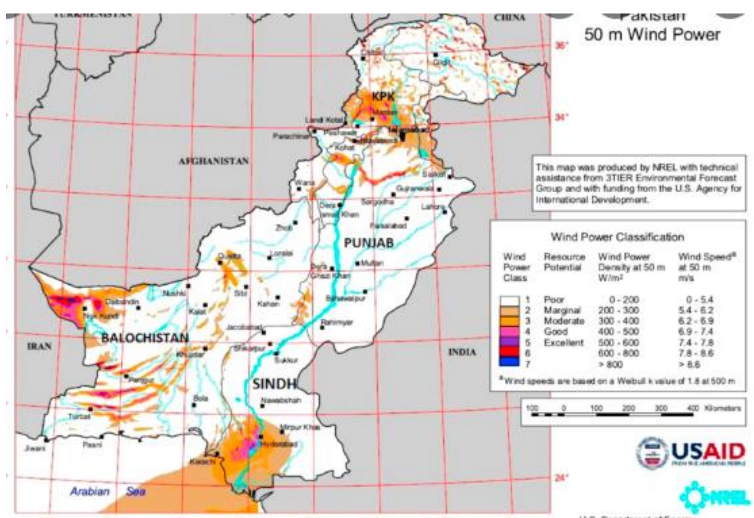
5.1 Recommendations

Following are the recommendations for any future work in this area:

- The turbine can be smartly incorporated into the light poles that are used for streetlights on the highway in collaboration with the national highway authority which will reduce the frame cost to zero.
- The procurement of a special generator with rated power appropriate for the specific turbine can improve the results manifold.
- To avoid high torques and dynamic stall, we can do some advancements in the design by either pitch regulation or the double-helical complex design in which each segment of the blade is in some coordinate angle of a circle and at any instant, the rotor is experiencing all angles of attack. This design, however, gets very complicated and is not doable by undergraduate students. The pitch regulation model using slats is a more viable and economic option that can be looked into.

- The Hybrid Savonius-Darrieus turbine is also an attractive model which is the talk of the day. This is also a bit complicated but is recommended to be brought under consideration.
- We used balsa wood for our design as it was easily available and fulfilled the design requirements, however, if manufactured on an industrial scale, we can imply the use of a smoother profile which can give us maximized results even greater than those achieved in the current experiment procedures.
- Students working further on the VAWT project should look for a better blade design, possibly a curved blade that requires more expertise and can result in better efficiency results even without slats.
- Further research on the possibility of a hybrid Savonius-Darrieus turbine can be made and more information can be collected to allow discussion of slats at 45 degrees which introduces an aspect of drag base as well in our model. If this can be validated, it can serve as a breakthrough.

Wind Potential Interpretation:



From the results we obtained, we can assume that the model can be implemented only where there is an additional boost from wind energy in Pakistan. As we have seen that the turbine works from the wind gust that is generated by the moving cars; on the other hand, if we find a suitable area for implementing this concept, then we can extract the maximum energy out of it.

Limitations:

- As Pakistan is a developing country and most of the manufacturing techniques are not available here. The manufacturing of a turbine was quite a hectic process and we had to put an additional effort into the procurement of material. For that purpose, we utilized the sources available in NUST labs and imported a few parts as well. However, to have a sustainable business as described above, the issue of material procurement should be resolved here and we need to find a better way to narrow the supply chain gap in Pakistan.

- Another problem we faced was in the simulations and the software side of this project. The resources we utilized to serve the purpose were limited as we had to use the computers of our labs. Their processing power was not enough to compute the overall 3-D analysis of the turbine which could have provided us with better results.

Future Roadmap:

This project can find its grounds in future projects and can be a forerunner of many innovations as well. As the world is moving towards sustainability, we can implement this type of business model for sustainable energy, and to serve that purpose, the newly build housing societies and motorways of Pakistan can also be utilized.

Also, as a project, this FYP has taught us many things which include the use of engineering knowledge in an efficient way. And not just that, it has also taught us how can we use our engineering knowledge and convert its insights into a business. Many startups are working on sustainable energy in Pakistan and seeing this loophole that no one is working on a turbine-based technology here boosted us to implement this concept. Although, it is very hard to go against the flow and initiate something that has never been implemented in Pakistan yet, seeing this as a perfect opportunity for business can also pave the way towards fruitful inventions.

Sustainability & VAWT:

Although this technology can not serve the energy needs of our country; yet seeing the potential of utilizing energy where there is a huge gap of it and still needs to be implemented can ensure its maximum usage. Lahore-Islamabad motorway gets dark during the night time causing difficulty for the drivers to drive. By using this, the single light can be charged from the same turbine and does not need to be changed afterwards. So this concept proves the sustainability in this solution as well.

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APPENDIX 1: Tables

Principal dimensions			Basic load ratings		Fatigue load limit	Speed ratings		Mass	Designations	
			dynamic	static		Reference speed	Limiting speed[1)]		Bearing open or capped on both sides	capped on one side[1)]
d	D	B	C	C_0	P_u					
mm			kN		kN	r/min		kg	–	
15 cont.	32	9	5,85	2,85	0,12	50 000	26 000	0,032	▸ 6002-2Z	6002-Z
	32	13	5,59	2,85	0,12	–	14 000	0,039	63002-2RS1	–
	35	11	8,06	3,75	0,16	43 000	28 000	0,045	▸ 6202	–
	35	11	8,06	3,75	0,16	–	13 000	0,046	▸ 6202-2RSH	6202-RSH
	35	11	8,06	3,75	0,16	43 000	22 000	0,046	▸ 6202-2RSL	6202-RSL
	35	11	8,06	3,75	0,16	43 000	22 000	0,048	▸ 6202-2Z	6202-Z
	35	14	7,8	3,75	0,16	–	13 000	0,054	62202-2RS1	–
	42	13	11,9	5,4	0,228	38 000	24 000	0,082	▸ 6302	–
	42	13	11,9	5,4	0,228	–	12 000	0,085	▸ 6302-2RSH	6302-RSH
	42	13	11,9	5,4	0,228	38 000	19 000	0,085	▸ 6302-2RSL	6302-RSL
	42	13	11,9	5,4	0,228	38 000	19 000	0,086	▸ 6302-2Z	6302-Z
	42	17	11,4	5,4	0,228	–	12 000	0,11	62302-2RS1	–
	52	7	4,49	3,75	0,16	–	7 500	0,034	▸ 61808-2RS1	–
17	26	5	2,03	1,27	0,054	–	16 000	0,0082	▸ 61803-2RS1	–
	26	5	2,03	1,27	0,054	56 000	28 000	0,0082	61803-2RZ	–
	26	5	2,03	1,27	0,054	56 000	28 000	0,0082	▸ 61803-2Z	–
	26	5	2,03	1,27	0,054	56 000	34 000	0,0075	▸ 61803	–
	30	7	4,62	2,55	0,108	–	14 000	0,017	▸ 61903-2RS1	–
	30	7	4,62	2,55	0,108	50 000	26 000	0,017	▸ 61903-2Z	–
	30	7	4,62	2,55	0,108	50 000	26 000	0,018	61903-2RZ	–
	30	7	4,62	2,55	0,108	50 000	32 000	0,016	▸ 61903	–
	35	8	6,37	3,25	0,137	45 000	22 000	0,032	▸ 16003-2Z	–
	35	8	6,37	3,25	0,137	45 000	28 000	0,031	▸ 16003	–
	35	10	6,37	3,25	0,137	45 000	28 000	0,038	▸ 6003	–
	35	10	6,37	3,25	0,137	–	13 000	0,039	▸ 6003-2RSH	6003-RSH
	35	10	6,37	3,25	0,137	45 000	22 000	0,039	▸ 6003-2RSL	6003-RSL
	35	10	6,37	3,25	0,137	45 000	22 000	0,041	▸ 6003-2Z	6003-Z
	35	14	6,05	3,25	0,137	–	13 000	0,052	63003-2RS1	–
	40	12	9,95	4,75	0,2	38 000	24 000	0,065	▸ 6203	–

Appendix 2: Simulations

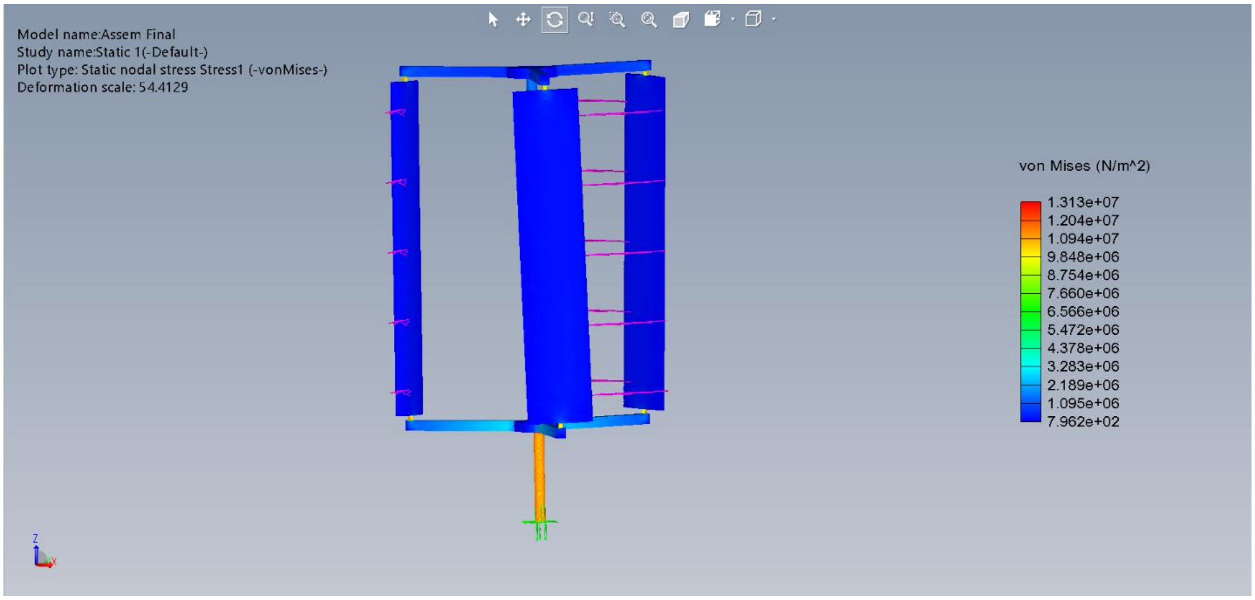

Figure 36: Simulation in 3D

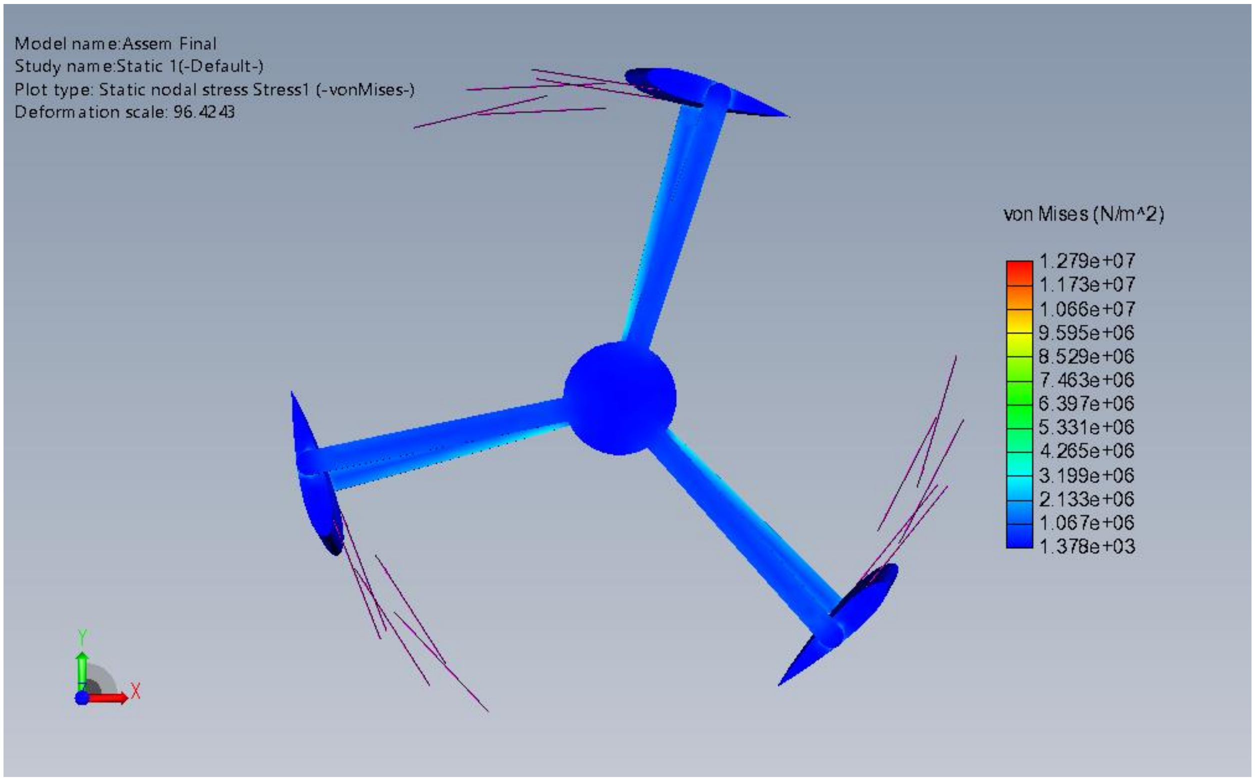

Figure 37: Simulation in 2D

Appendix 3: Simulation Data

Airfoil Curve Points: X, Y

NACA 0012

X	Y	X	Y	X	Y
1.00000	0.00126	0.65434	0.04093	0.21951	0.05836
0.99280	0.00227	0.62492	0.04354	0.19760	0.05723
0.97989	0.00405	0.59547	0.04600	0.17661	0.05581
0.96352	0.00627	0.56607	0.04832	0.15660	0.05410
0.94455	0.00878	0.53680	0.05047	0.13760	0.05211
0.92350	0.01151	0.50774	0.05245	0.11965	0.04983
0.90075	0.01438	0.47895	0.05422	0.10280	0.04729
0.87658	0.01735	0.45050	0.05578	0.08709	0.04450
0.85123	0.02038	0.42246	0.05712	0.07256	0.04145
0.82489	0.02343	0.39488	0.05822	0.05924	0.03817
0.79774	0.02648	0.36782	0.05906	0.04717	0.03467
0.76991	0.02950	0.34135	0.05965	0.03639	0.03096
0.74154	0.03248	0.31551	0.05996	0.02694	0.02705
		0.29035	0.06000	0.01885	0.02296

0.00308	0.00965	0.19760	-0.05723	0.71275	-0.03539
0.00078	0.00490	0.21951	-0.05836	0.74154	-0.03248
0.00000	0.00000	0.24231	-0.05920	0.76991	-0.02950
0.00078	-0.00490	0.26594	-0.05974	0.79774	-0.02648
0.00308	-0.00965	0.29035	-0.06000	0.82489	-0.02343
0.00688	-0.01425	0.31551	-0.05996	0.85123	-0.02038
0.01215	-0.01869	0.34135	-0.05965	0.87658	-0.01735
0.01885	-0.02296	0.36782	-0.05906	0.90075	-0.01438
0.02694	-0.02705	0.39488	-0.05822	0.92350	-0.01151
0.03639	-0.03096	0.42246	-0.05712	0.94455	-0.00878
0.04717	-0.03467	0.45050	-0.05578	0.96352	-0.00627
0.05924	-0.03817	0.47895	-0.05422	0.97989	-0.00405
0.08709	-0.04450	0.53680	-0.05047	1.00000	-0.00126
0.10280	-0.04729	0.56607	-0.04832		
0.11965	-0.04983	0.59547	-0.04600		
0.13760	-0.05211	0.62492	-0.04354		
0.15660	-0.05410	0.65434	-0.04093		
0.17661	-0.05581	0.68365	-0.03821		

NACA 0015

1.00000	0.00157
0.99280	0.00283
0.97989	0.00506
0.96352	0.00783
0.94455	0.01098
0.92350	0.01439
0.90075	0.01798
0.87658	0.02169
0.85123	0.02548
0.82489	0.02929
0.79774	0.03310
0.76991	0.03688
0.74154	0.04060
0.56607	0.06040
0.53680	0.06309
0.50774	0.06556
0.47895	0.06777
0.45050	0.06973
0.42246	0.07140
0.39488	0.07277
0.36782	0.07383
0.34135	0.07456
0.31551	0.07495
0.29035	0.07500
0.26594	0.07468
0.24231	0.07400
0.21951	0.07296
0.10280	0.05912
0.08709	0.05562
0.07256	0.05182
0.05924	0.04772
0.04717	0.04334
0.03639	0.03870
0.02694	0.03381
0.01885	0.02870
0.01215	0.02336
0.00688	0.01781
0.00308	0.01207
0.00078	0.00613
0.00000	0.00000
0.00078	-0.00613

0.03639	-0.03870	0.42246	-0.07140	0.94455	-0.01098
0.04717	-0.04334	0.45050	-0.06973	0.96352	-0.00783
0.05924	-0.04772	0.47895	-0.06777	0.97989	-0.00506
0.07256	-0.05182	0.50774	-0.06556	0.99280	-0.00283
0.08709	-0.05562	0.53680	-0.06309	1.00000	-0.00157
0.10280	-0.05912	0.56607	-0.06040		
0.11965	-0.06229	0.59547	-0.05751		
0.13760	-0.06513	0.62492	-0.05442		
0.15660	-0.06763	0.65434	-0.05117		
0.17661	-0.06977	0.68365	-0.04776		
0.19760	-0.07154	0.71275	-0.04423		
0.21951	-0.07296	0.74154	-0.04060		
0.24231	-0.07400	0.76991	-0.03688		
0.26594	-0.07468	0.79774	-0.03310		
0.29035	-0.07500	0.82489	-0.02929		
0.31551	-0.07495	0.85123	-0.02548		
0.34135	-0.07456	0.87658	-0.02169		
0.36782	-0.07383	0.90075	-0.01798		
0.39488	-0.07277	0.92350	-0.01439		

NACA 0018

1.00000	0.00189
0.99280	0.00340
0.97989	0.00607
0.96352	0.00940
0.94455	0.01318
0.92350	0.01727
0.90075	0.02158
0.87658	0.02603
0.85123	0.03057
0.82489	0.03515
0.79774	0.03972
0.76991	0.04426
0.74154	0.04872
0.71275	0.05308
0.68365	0.05732
0.65434	0.06140
0.62492	0.06530
0.56607	0.07248
0.53680	0.07571
0.50774	0.07867
0.47895	0.08133
0.45050	0.08367
0.42246	0.08568
0.39488	0.08733
0.36782	0.08860
0.34135	0.08947
0.31551	0.08994
0.29035	0.09000
0.26594	0.08962
0.24231	0.08880
0.21951	0.08755
0.19760	0.08585
0.17661	0.08372
0.15660	0.08115
0.13760	0.07816
0.10280	0.07094
0.08709	0.06674
0.07256	0.06218
0.05924	0.05726
0.04717	0.05201
0.03639	0.04644
0.02694	0.04058
0.01885	0.03443
0.01215	0.02803
0.00688	0.02137
0.00308	0.01448
0.00078	0.00735
0.00000	0.00000
0.00078	-0.00735
0.00308	-0.01448
0.00688	-0.02137
0.01215	-0.02803
0.01885	-0.03443

0.03639	-0.03870
0.04717	-0.04334
0.05924	-0.04772
0.07256	-0.05182
0.08709	-0.05562
0.10280	-0.05912
0.11965	-0.06229
0.13760	-0.06513
0.15660	-0.06763
0.17661	-0.06977
0.19760	-0.07154
0.21951	-0.07296
0.24231	-0.07400
0.26594	-0.07468
0.29035	-0.07500
0.31551	-0.07495
0.34135	-0.07456
0.36782	-0.07383
0.39488	-0.07277
0.42246	-0.07140
0.45050	-0.06973
0.47895	-0.06777
0.50774	-0.06556
0.53680	-0.06309
0.56607	-0.06040
0.59547	-0.05751
0.62492	-0.05442
0.65434	-0.05117
0.68365	-0.04776
0.71275	-0.04423
0.74154	-0.04060
0.76991	-0.03688
0.79774	-0.03310
0.82489	-0.02929
0.85123	-0.02548
0.87658	-0.02169
0.90075	-0.01798
0.92350	-0.01439
0.94455	-0.01098
0.96352	-0.00783
0.97989	-0.00506
0.99280	-0.00283
1.00000	-0.00157

NACA 0018

1.00000	0.00189	0.56607	0.07248	0.10280	0.07094
0.99280	0.00340	0.53680	0.07571	0.08709	0.06674
0.97989	0.00607	0.50774	0.07867	0.07256	0.06218
0.96352	0.00940	0.47895	0.08133	0.05924	0.05726
0.94455	0.01318	0.45050	0.08367	0.04717	0.05201
0.92350	0.01727	0.42246	0.08568	0.03639	0.04644
0.90075	0.02158	0.39488	0.08733	0.02694	0.04058
0.87658	0.02603	0.36782	0.08860	0.01885	0.03443
0.85123	0.03057	0.34135	0.08947	0.01215	0.02803
0.82489	0.03515	0.31551	0.08994	0.00688	0.02137
0.79774	0.03972	0.29035	0.09000	0.00308	0.01448
0.76991	0.04426	0.26594	0.08962	0.00078	0.00735
0.74154	0.04872	0.24231	0.08880	0.00000	0.00000
0.71275	0.05308	0.21951	0.08755	0.00078	-0.00735
0.68365	0.05732	0.19760	0.08585	0.00308	-0.01448
0.65434	0.06140	0.17661	0.08372	0.00688	-0.02137
0.62492	0.06530	0.15660	0.08115	0.01215	-0.02803
		0.13760	0.07816	0.01885	-0.03443

0.03639	-0.04644
0.04717	-0.05201
0.05924	-0.05726
0.07256	-0.06218
0.08709	-0.06674
0.10280	-0.07094
0.11965	-0.07475
0.13760	-0.07816
0.15660	-0.08115
0.17661	-0.08372
0.19760	-0.08585
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0.56607	-0.07248
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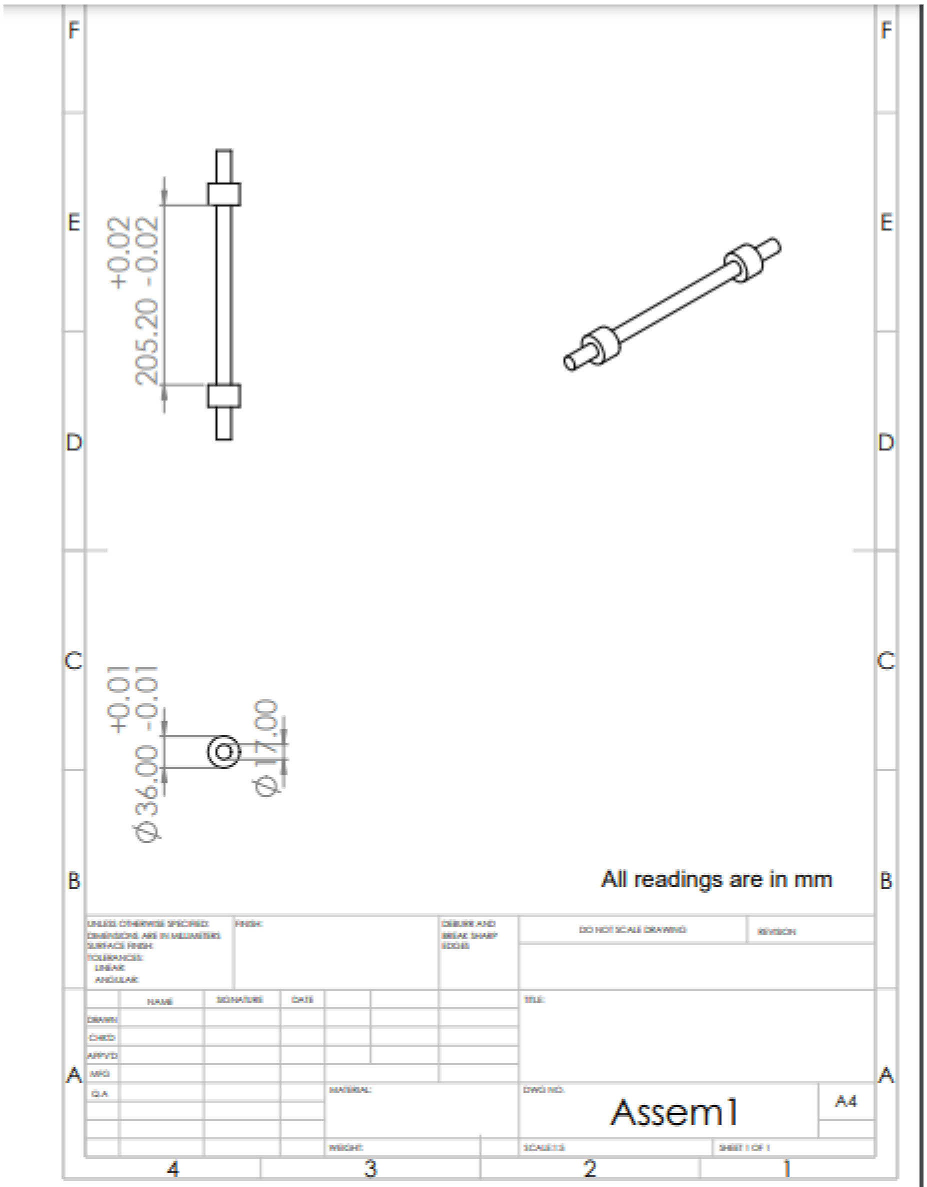
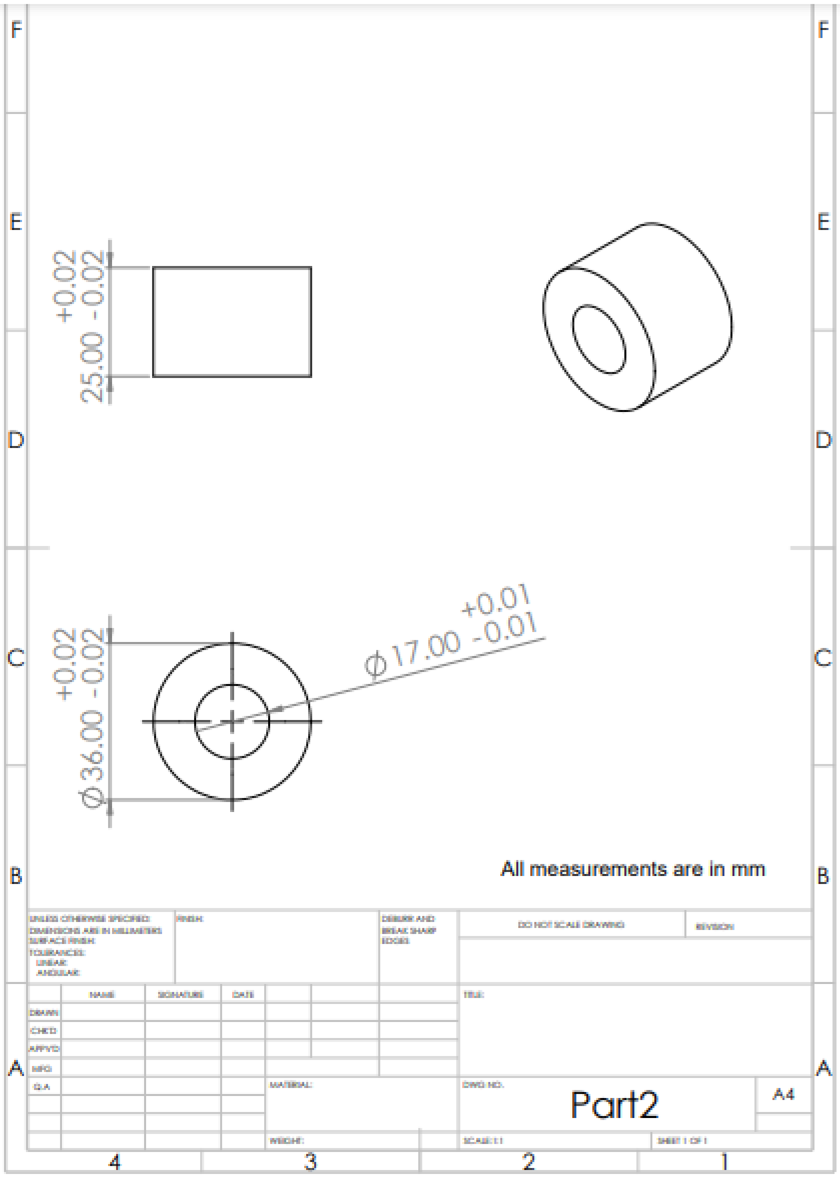
0.62492	-0.06530
0.65434	-0.06140
0.68365	-0.05732
0.71275	-0.05308
0.74154	-0.04872
0.76991	-0.04426
0.79774	-0.03972
0.82489	-0.03515
0.85123	-0.03057
0.87658	-0.02603
0.90075	-0.02158
0.92350	-0.01727
0.94455	-0.01318
0.96352	-0.00940
0.97989	-0.00607
0.99280	-0.00340
1.00000	-0.00189

Appendix 4: Engineering Drawings





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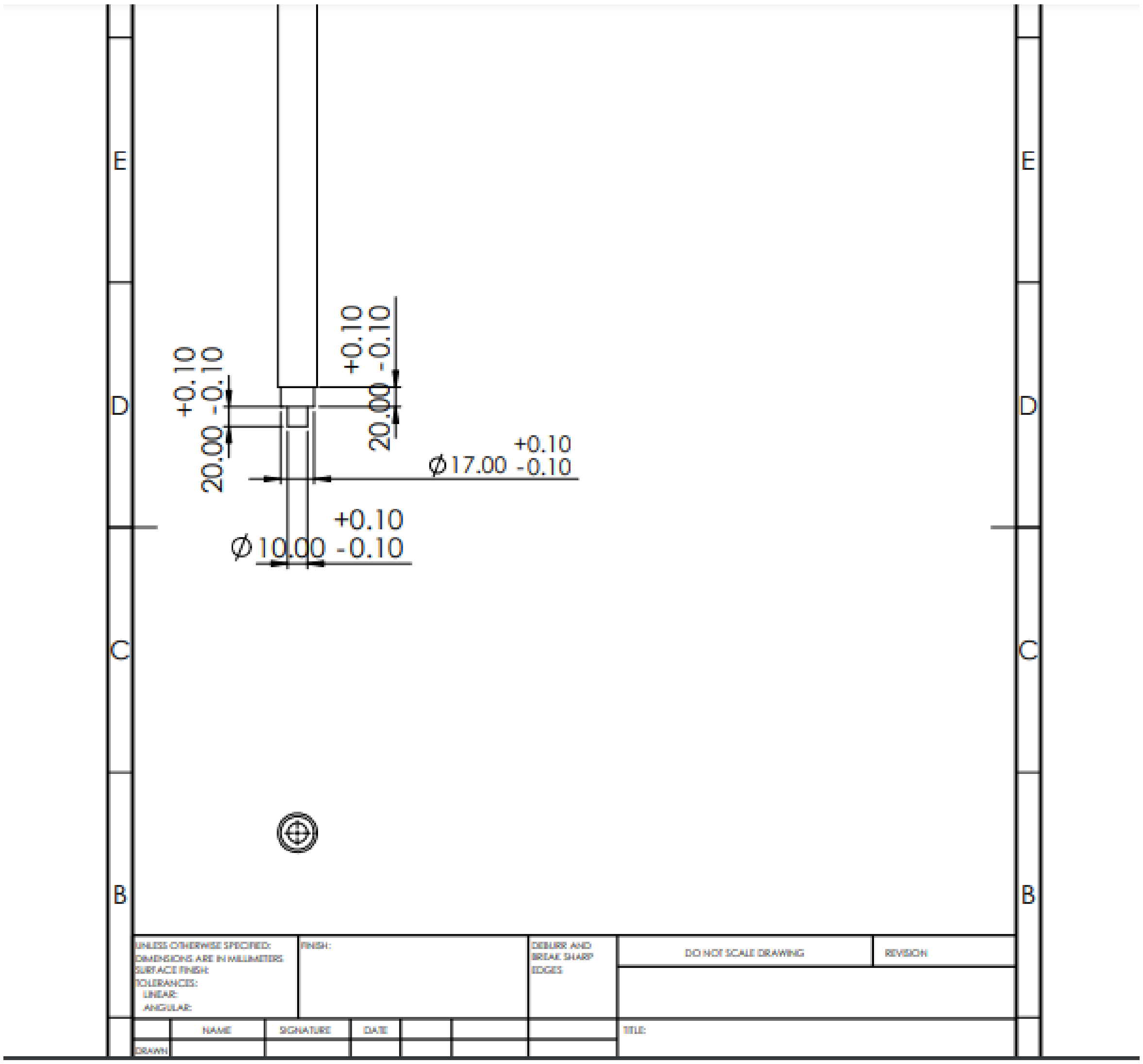
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
TITLE:
MATERIAL:
DWG NO.
Part2
A4
WEIGHT:
SCALE:1:1
SHEET 1 OF 1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DIMENSIONS ARE IN MILLIMETERS
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LINEAR:
ANGULAR:
FINISH:
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BREAK SHARP
EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
TITLE: