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Design and Development of Savonius Vertical Axis Wind Turbine

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DECLARATION

we hereby declare that this thesis project entitled “**Design and development of Savonius vertical axis wind turbine**” in partial fulfillment of the requirements for the award of the degree of Master of Science in automotive Technology Teacher Education is the result of our own research except as cited in references. The work carried out from March 2015 to June 2015 under the supervision of N. Ramesh Babu (Associate Professor) Department of Mechanical and Vehicle Engineering, Adama Science and Technology University. The matter embodied in thesis project has not been accepted for any degree and is not submitted in candidature of any other degree or diploma.

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I hereby declare I have read this project and in my opinion this thesis project is sufficient in terms of scope and quality. This thesis project has been submitted for examination with my approval.

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(Major Advisor) Signature Date

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LIST OF ACRONYMS, ABBREVIATIONS

MW	Mega Watt
AC	Alternative current
US	United States
EU	European Union
PVC	Polyvinyl chloride
HAWT	Horizontal Axis Wind Turbine
VAWT	Vertical Axis Wind Turbine
NMSA	National Meteorological Service Agency
EEPCo	Ethiopian Electric Power Corporation
EPA	Environmental Protection Authority of Ethiopia
WPP	Wind Power Plant
PPP	Project Power Plant
NACA	National Advisory Committee for Aeronautics
AWSPY	Average Wind Speed per Year
RPM	Revolution Per Minute
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CFD	Computational Fluid Dynamics
ASME	American Standard Material Engineering

ABSTRACT

We know that there is enough wind globally to satisfy much, or even most, of humanity's energy requirements – if it could be harvested effectively and on a large scale. This paper presents the design and development of the Savonius VAWT to generate 2.5 kW power output. The relevant design parameters and theories were studied in this paper and used to determine related dimension geometry and requirements of the Savonius VAWT. The Savonius rotor was dimensioned with the rotor diameter of 5.517 m and the rotor height of 11.034 m. The 3D model of Savonius rotor blade was created by using Solid Works software. Computational Fluid Dynamics (CFD) analysis and structural Finite Element Analysis (FEA) are presented in this paper. CFD analysis was performed to obtain the pressure difference between concave and convex region of the blade.

Keywords: *Savonius, Renewable Energy, Wind, Wind Turbines, generator, Rotor Blade, CFD,*

1. INTRODUCTION

1.1 Back ground of the study

In this modern age more and more energy is required for daily consumption in all walks of life. Sources and quantum of fossil energy are dwindling day by day and getting exhausted at a very fast rate. Hence conservation, tapping new sources of energy and harnessing of the same from the various non-conventional sources, is an important aspect of energy production/conservation and utilization all over the world. The sky-rocketing price of crude oil has ruined the economy of many a country, hence there is a crying need for production of energy from non-conventional sources at the earliest. The present concept is one of the answers to this problem, as the said induced wind into useable electric energy which can be utilized straight away.

Energy resources in our modern fast paced world are fast depleting, hence it is indispensible that we find new ways of generating energy which is both self- sustaining as well as easily manageable. Wind energy has long been used to generate electricity through wind turbines, and has proved to be one of the most reliable renewable sources of energy in many countries of the world. However since there are very few regions in the world that experience windy conditions throughout a year, this method becomes restricted to only a few chosen regions. For example in Ethiopia, Mekelle and Adama.

The fixed wind powered electricity generation systems in use, till now are dependent on wind direction and the force of the wind. The same concept is used in this project, using Savonius vertical axis wind turbine for generate electricity a place at which have low wind speed.

2.2. Power and Energy in Wind

The main source of the earth's power is from the sun and it is approximately$1.484x10^{18}$ KWh/year. Only 2.5% of this energy is said to be converted into energy of motion of atmosphere. Therefore, the total kinetic energy of the air, which is related to wind, can be estimated as $2.5x10^{14}$ KWh. Most of this power is stored in very high altitudes usually 8km to 14km from the ground level. While the average wind speed is about 3 to 14 m/s around the surface of the earth, it is about 18 to 26 m/s above 8km high. However, because of turbulences in the air, the high wind speeds can also be seen in the lower layers of atmosphere [29].

The force of the wind can be very strong, as can be seen after the passage of a hurricane or a typhoon. Historically, people have harnessed this force peacefully, its most important usage probably being the propulsion of ships using sails before the invention of the steam engine and the internal combustion engine. Wind has also been used in windmills to grind grain or to pump water for irrigation. At the beginning of the twentieth century electricity came into use and windmills gradually became wind turbines as the rotor was connected to an electric generator. A country or region where energy production is based on imported coal or oil will become more self-sufficient by using alternatives such as wind power. Electricity produced from the wind produces no CO_2 emissions and therefore does not contribute to the greenhouse effect. Wind energy is relatively labor intensive and thus creates many jobs.

Actually, a total of 8,484 MW wind power capacity was installed in the EU in 2008, figure 1. This puts wind energy ahead of any other power technology for the first time. The 36% of all new electricity producing capacity installed in the EU in 2008 was wind energy followed by natural gas (6,932 MW - 29%), oil (2,495 MW - 10%), coal (762 MW - 3%) and hydro (473 MW - 2%) [7]

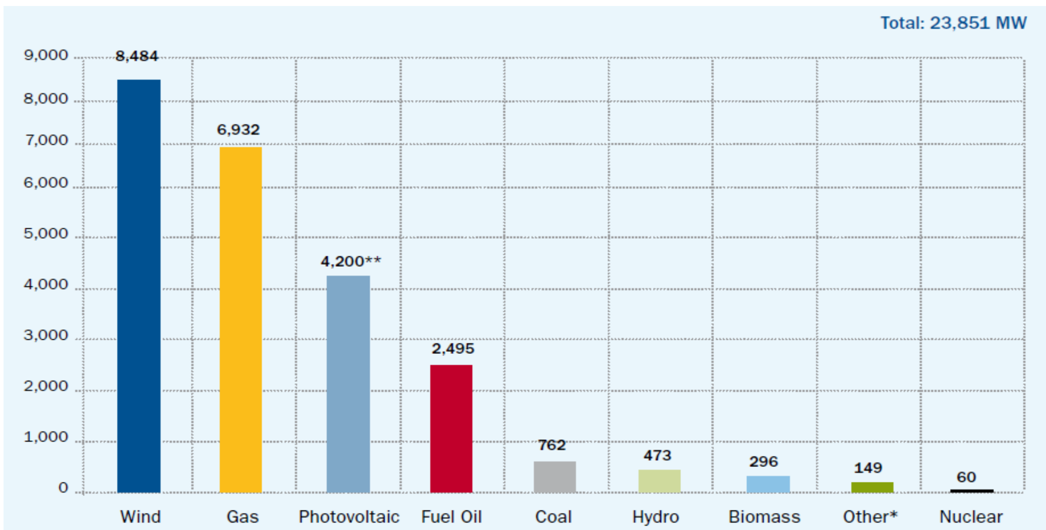


Figure 1 New power capacity installed in 2008 [7]

The Kinetic Power in a moving air stream is given by

$$KP = \tfrac{1}{2} \rho A V^3 \qquad (2)$$

Where

KP = Power in Wind, (Watts)

ρ = Air density (1.225 kg/m^3 at 15°C, 1.0132 bar)

A= Cross-sectional flow area (m^2)

V = Wind speed (m/s)

Note: Power is proportional to the CUBE of wind speed.

Average power is not linearly proportional to the average wind speed.

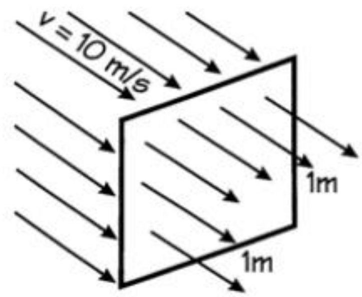
$$KP_{ave} = 6/\pi\ (½\ r\ AV_{ave}^{3})$$

The term, 6/ π, accounts for the distribution of wind speed, and hence kinetic power with wind with time. Average power is not linearly proportional to the average wind speed

e,g., a 10 m/s wind blowing through a 1m^2 window

$$KPave = 6/\pi\ (½\ 1.225 \times 1 \times 10^{3})$$

$$= 1170\ W = 1.17\ kW$$



There is an optimum condition where the product of the wind speed decrease and flow rate is maximum. This known as the BETZ LIMIT and is 59.2% of the inflowing kinetic power. On average, good wind turbines extract about half of the theoretical maximum or 30% of the power in the airstream that passes through the rotor [23], thus

$$P_{ave} = 0.3 \times 6/\pi\ (½\ r\ AV_{ave}^{3}) \quad = \quad 0.35\ AV_{ave} \qquad (3)$$

1.3 Statement of the problem

With ever increasing population the demand for primary energy is growing at a rapid rate year by year. And also demand for oil is rising. So there is a need to find additional energy source. With increasing environmental concern, and approaching limit to fossil fuel consumption, wind power has regained interest as a renewable energy source. New generation of wind mills produce electric power and are more generally used for all applications, which require power. But in the case of horizontal wind turbine air strikes is from one direction only, generator and gearbox cannot place on the ground, cost of erecting is high, need yaw system, control system is required. Therefore, there exists an immense need of a system for generating electricity from wind induced by Savonius vertical axis wind turbine, suitability for low values of wind speed and within a limited range, necessity of adequate speed control to keep the efficiency within acceptable values, high starting torque, low noise, operating at low wind speed, available throughout the year at various places and with sufficient force of wind. Therefore this project provides a solution to the problem for generating electricity in this manner.

1.4 Objectives

1.3.1 General Objective

The general objective of this project is to design and develop a prototype of Savonius vertical axis wind turbine.

1.3.2 Specific objectives

- ✓ To design Savonius vertical axis wind turbine.
- ✓ To make a cad model of vertical axis wind turbine.
- ✓ To develop prototype of wind turbine.
- ✓ To demonstrate the electricity generation from local wind.

1.5 Significance of the project

Small turbines can be used to generate more power and can be used for commercial applications. The basic model of the design output of this project, generating electricity by local wind for providing additional power to the country. It also helps

- ✓ To increase the acceptance of wind from any direction thus eliminating the need for reorientation;

- ✓ To reduce the usage of conventional resources of power.
- ✓ To gain the output relatively at low operating speed (rpm)
- ✓ For easy and cheap to construct
- ✓ To reduce carbon emissions and also assists the government in saving on fuel too…
- ✓ To expand our industrialization programs
- ✓ To reduce shortage of power especially for the rural area

1.6. Scope of the project

This project is concentrates to basic design and development of prototype to utilize the available wind resources and to reduce the usage of non-renewable energy resources.

1.7 Limitation of the study

Due to the unpopularity of the project in Ethiopia especially in the project area no such turbines install, the time and budget also limit the study.

1.8 Organization of the study

Chapter two of this paper contains the theoretical frame work, chapter three discusses the materials and methods to perform the project, chapter four will give a discussion of the results and finally in chapter five conclusions are drawn from measurement, followed by recommendation.

2. LITERATURE REVIEW

2.1. Introduction

Life is nothing but a continuous process of energy conversion and transformation. The accomplishments of civilization have largely been achieved through the increasingly efficient and extensive harnessing of various forms of energy to extend human capabilities and ingenuity. Energy is similarly indispensable for continued human development and economic growth. Providing adequate, affordable energy is essential for eradicating poverty, improving human welfare, and raising living standards world-wide. And with-out economic growth, it will be difficult to address environmental challenges, especially those associated with poverty. But energy production, conversion, and use always generate undesirable by-products and emissions at least in the form of dissipated heat. Energy cannot be created or destroyed, but it can be converted from one form to another. Although it is common to discuss energy consumption, energy is actually transformed rather than consumed. What is consumed is the ability of oil, gas, coal, biomass, or wind to produce useful work [20]. In this thesis, an attempt is made to convert wind energy one of the renewable energy sources in to electric energy.

2.2. Renewable energy

The utilization of renewable energy sources is not at all new; in the history of mankind renewable energies have for a long time been the primary possibility of generating energy. This only changed with industrial revolution when lignite and hard coal became increasingly important. Later on, also crude oil gained importance. Offering the advantages of easy transportation and processing, crude oil has become one of the prime energy carriers applied today. As fossil energy carriers were increasingly used for energy generation, at least by the industrialized countries, the application of renewable energies decreased in absolute and relative terms; besides a few exceptions, renewable energies are of secondary importance with regard to overall energy generation. Yet, the utilization of fossil energy carriers involves a series of undesirable side effects which are less and less tolerated by industrialized societies increasingly sensitized to possible environmental and climate effects at the beginning of the 21st century. This is why the search for environmental, climate-friendly and socially acceptable, alternatives suitable to cover the energy demand has become increasingly important. Also with regard to the considerable price increase for fossil fuel energy on the global energy markets in the last few years, not only in Europe, high hopes and expectations are placed on the multiple possibilities of utilizing renewable sources of energy. Considering this background, the present chapter aims at presenting the physical and technical principles for using wind and wave energy [15].

Unlike fossil fuels, Renewable energy are in exhaustible, renewable energy sources regenerate and can be sustained indefinitely. The effective renewable sources used most often are: Biomass (including wood and wood waste, municipal solid waste, land fill gas, biogas, ethanol, and biodiesel), Hydropower (including tidal, water potential and ocean wave energy), geothermal wind and solar energy.

The use of renewable energy is not new. More than 150 years ago, wood, which is one form of biomass, supplied up to 90% of our energy needs. Today, we are looking again at renewable sources to find new ways to use them to help meet our energy needs (see Fig.2). In 2006, about 18% of global final energy consumption came from renewable energies, with 13% coming from traditional biomass, which is mainly used for heating, and 3% from hydroelectricity. New renewables (small hydropower installations, modern biomass, wind, solar, geothermal, and biofuels) accounted for another 2.4% and are growing very rapidly [11].

The share of renewables in electricity generation is around 18%, with 15% of global electricity coming from hydroelectricity and 3.4% from new renewables.

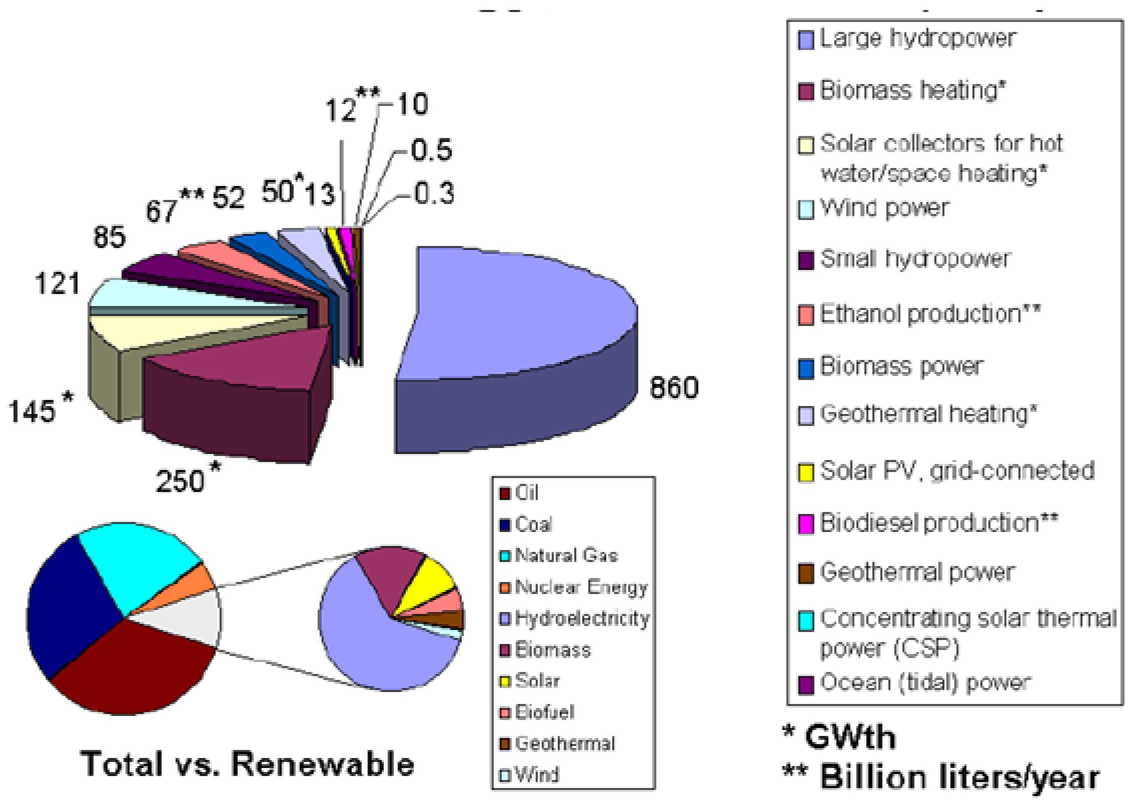


Figure 2 2008 worldwide renewable energy sources. Source: [14].

2.3. Historical development of wind energy

The use of wind energy dates back to ancient times when it was employed to propel sailboats. Extensive application of wind turbines seems to have originated in Persia where it was used for grinding wheat. The Arab conquest spread this technology throughout the Islamic world and China. In Europe, the wind turbine made its appearance in the eleventh century. Two centuries later it had become an important tool, especially in Holland.

The development of the American West was aided by wind-driven pumps and sawmills. The first significant wind turbine designed especially for the generation of electricity was built by Charles Brush in Cleveland, Ohio. It operated for 12 years, from 1888 to 1900 supplying the needs of his mansion.

Charles Brush was a mining engineer who made a fortune with the installation of arc lights to illuminate cities throughout the United States.

His wind turbine was of the then familiar multi-vane type (it sported 144 blades) and, owing to its large solidity, rotated rather slowly and required gears and transmission belts to speed up the rotation by a factor of 50 so as to match the speciation of the electric generator. The wind turbine itself had a diameter of 18.3 meters and its hub was mounted 16.8 meters above ground.

The tower was mounted on a vertical metal pivot so that it could orient itself to face the wind. The whole contraption massed some 40 tons. Owing to the intermittent nature of the wind, electric energy had to be stored in this case in 400 storage cells. Although the wind is free, the investment and maintenance of the plant caused the cost of electricity to be much higher than that produced by steam plants. Consequently, the operation was discontinued in 1900 and from then on the Brush mansion was supplied by the Cleveland utility. In 1939, construction of a large wind generator was started in Vermont. This was the famous Smith-Putnam machine, erected on a hill called Grandpa's Knob. It was a propeller-type device with a rated power of 1.3 MW at a wind speed of 15 m/s. Rotor diameter was 53 m. The machine started operation in 1941, feeding energy synchronously directly into the power network. Owing to blade failure, in March 1945, operation was discontinued. It ought to be mentioned that the blade failure had been predicted but during World War II there was no opportunity to redesign the propeller hub.

2.4. Wind energy basics

2.4.1. The Wind Resource

Wind is the movement of air caused by differential heating of the earth's surface. Air rises from the warmer surfaces and cooler is drawn in from the surrounding areas.

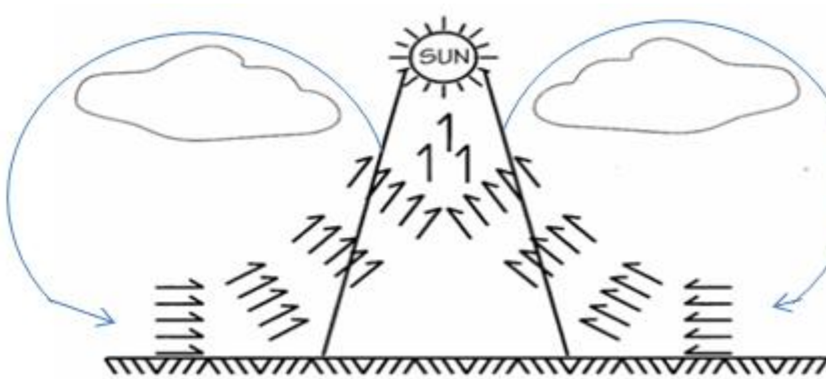


Figure 3: Schematic showing the **s**ource of wind energy

Wind is affected by topography; wind speed is affected by roughness and obstacles such as buildings and hills. Speed increases when approaching the obstacle and decreases and may separate and become turbulent of the downstream side.

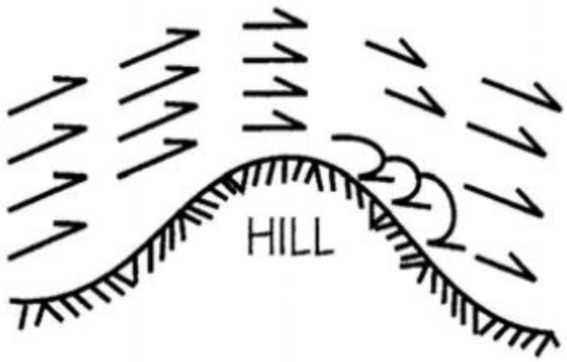


Figure 4: Factors of wind speed on hills

Wind turbines are often placed near the top of hills and ridges and well away from buildings and other structures.

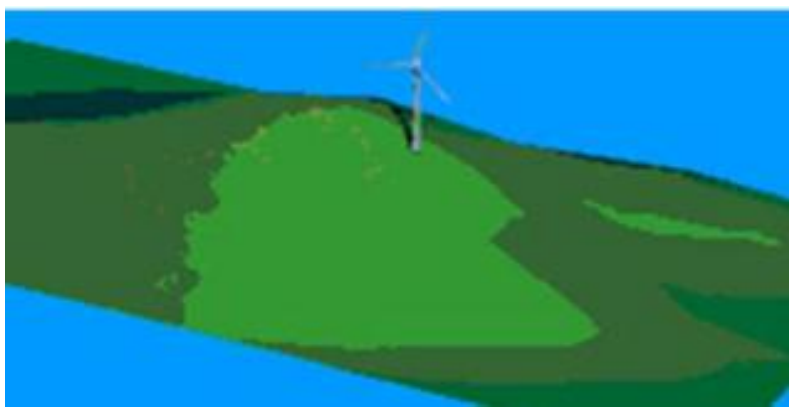


Figure 5: Schematic showing the wind turbine site at the top of a hill

The “windiness” of a particular site is described in terms of the Annual Average Wind Speed.

Table 1 Windiness of a particular site

Wind regime description	Annual average wind speed (m/s@ 10m)	Typical capacity factor
Poor	<4.0	0.25
Fair	4.0-5.0	0.3
Good	5.0-6.0	0.35
Very Good	6.0-7.0	0.4
Excellent	>7.0	0.45

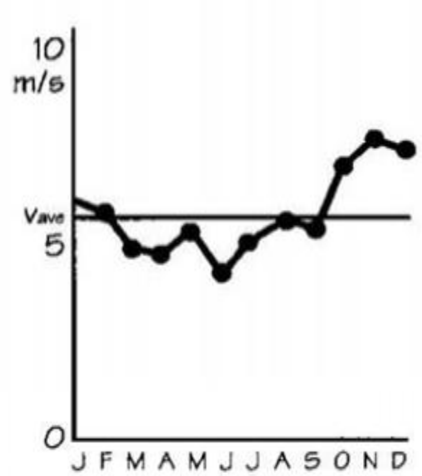


Figure 6 Windiness of a particular site

Rapid fluctuations in wind speed are called turbulence and may increase the structural and dynamic stresses on the wind turbine components. Thus it is not desirable to install turbines in areas of high turbulence. Near the earth’s surface wind speed is reduced by wind shear. The higher the wind turbine tower, the greater the wind velocity and therefore the annual average at this elevation is also higher.

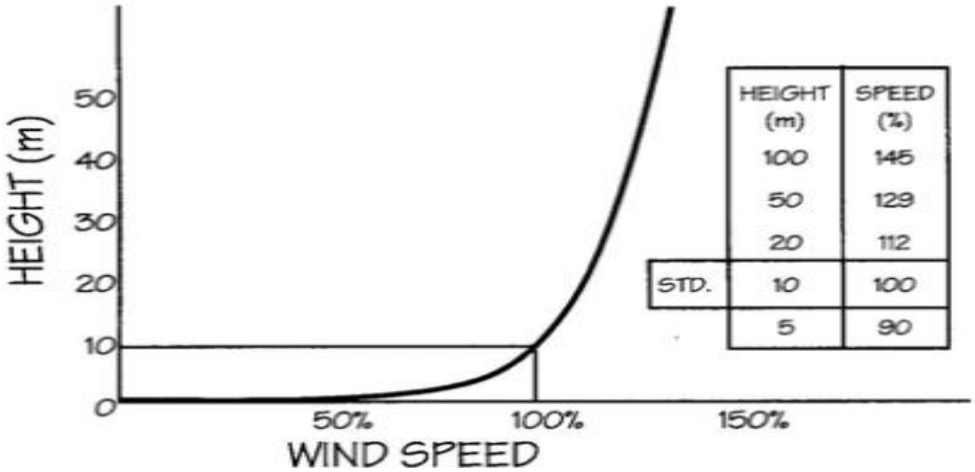


Figure 7 Comparison of wind speed with tower height

Wind speed is related to height by

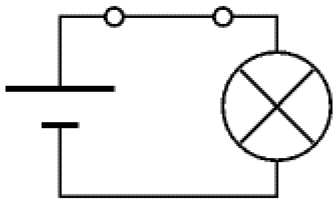
$$\frac{V_2}{V_1} = \left(\frac{H2}{H1}\right)^{\alpha} \qquad (1)$$

The exponent α depends on the type and roughness of the terrain. For flat land without major obstructions, α = 0.16 and wind speed increase 12% for every doubling of height.

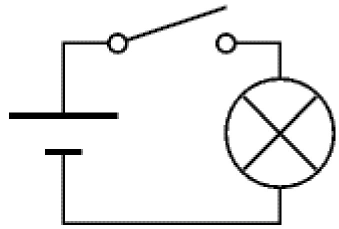
2.6. Voltage and Current

Voltage is the Cause, Current is the Effect

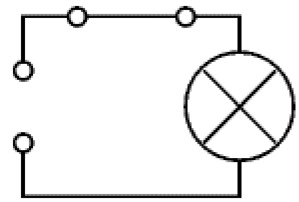
Voltage attempts to make a current flow, and current will flow if the circuit is complete. Voltage is sometimes described as the 'push' or 'force' of the electricity, it isn't really a force but this may help you to imagine what is happening. It is possible to have voltage without current, but current cannot flow without voltage.



(Fig.a) Voltage and Current
The switch is closed making a complete circuit so current can flow



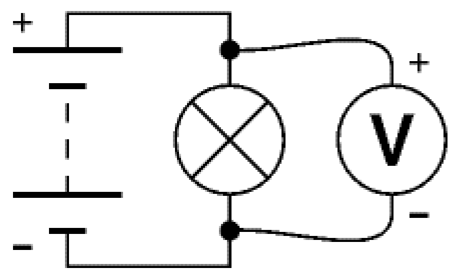
(Fig.b) Voltage but No Current
The switch is open so the circuit is broken and current cannot flow.



(Fig.c) No Voltage and No Current
Without the cell there is no source of voltage so current cannot flow.

Figure 8 Presence of voltage and current in a circuit

Voltage, V



- Connecting a voltmeter in parallel
- Voltage is a measure of the energy carried by the charge.
- The proper name for voltage is potential difference or p.d. for short, but this term is rarely used in electronics.
- Voltage is supplied by the battery (or power supply).
- Voltage is used up in components, but not in wires.
- Voltage across a component.
- Voltage is measured in volts, V.
- Voltage is measured with a voltmeter, connected in parallel.
- The symbol V is used for voltage in equations

Current, I

- ✓ Current is the rate of flow of charge.
- ✓ Current is not used up, what flows into a component must flow out.
- ✓ Current through a component.
- ✓ Current is measured in amps (amperes), A.
- ✓ Current is measured with an ammeter, connected in series.
- ✓ To connect in series you must break the circuit and put the ammeter across the gap, as shown in the diagram.
- ✓ The symbol I is used for current in equations.

1A (1 amp) is quite a large current for electronics, so mA (milliamps) are often used. m (milli) means "thousandth":

1mA = 0.001A, or 1000mA = 1A

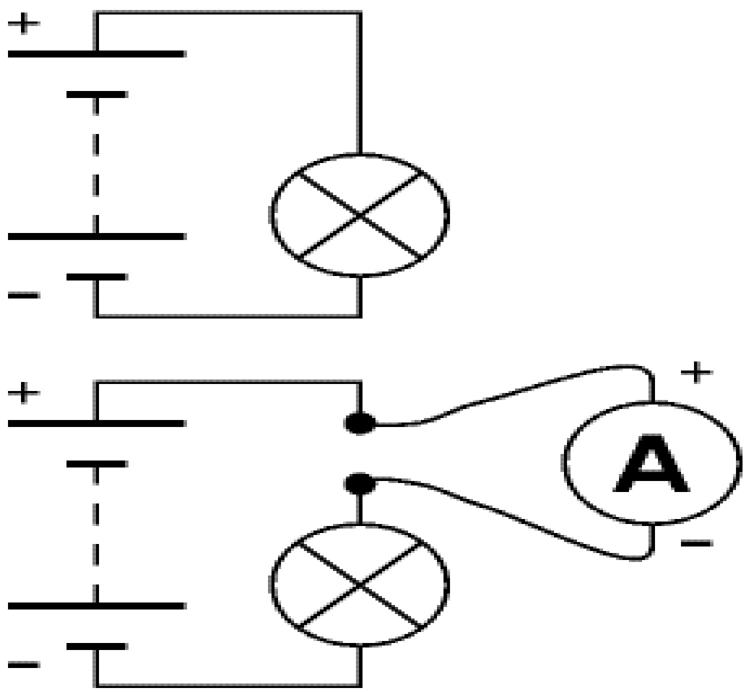
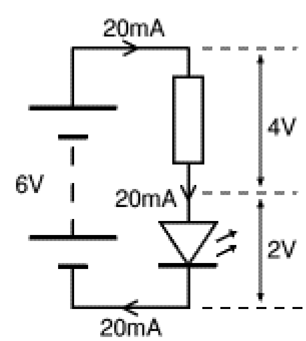


Figure 9: Connecting an ammeter in series



The need to break the circuit to connect in series means that ammeters are difficult to use on soldered circuits. Most testing in electronics is done with voltmeters which can be easily connected without disturbing circuits.

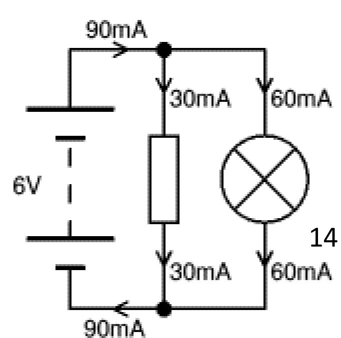
Voltage and Current for components in Series

Voltages add up for components connected in series. Currents are the same through all components connected in series.

In this circuit the 4V across the resistor and the 2V across the LED add up to the battery voltage: 2V + 4V = 6V.

The current through all parts (battery, resistor and LED) is 20mA.

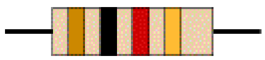
Voltage and Current for components in Parallel



Voltages are the same across all components connected in parallel. Currents add up for components connected in parallel.
In this circuit the battery, resistor and lamp all have 6V across them.

The 30mA current through the resistor and the 60mA current through the lamp add up to the 90mA current through the battery.

2.6.2. Resistors

Example:  Circuit symbol: 

Function

Resistors restrict the flow of electric current, for example a resistor is placed in series with a light-emitting diode (LED) to limit the current passing through the LED.

Connecting and soldering

Resistors may be connected either way round. They are not damaged by heat when soldering.

2.6.3. Ohm's Law

To make a current flow through a resistance there must be a voltage across that resistance. Ohm's Law shows the relationship between the voltage (V), current (I) and resistance (R). It can be written in three ways:

$$V = I \times R \quad \text{or} \quad I = \frac{V}{R} \quad \text{or} \quad R = \frac{V}{I} \tag{4}$$

where:	V = voltage in volts (V)	or:	V = voltage in volts (V)
	I = current in amps (A)		I = current in milliamps (mA)
	R = resistance in ohms (Ω)		R = resistance in kilo ohms (kΩ)

2.7. Generating Electricity by using wind energy

To make electricity, the shaft of the turbine must be connected to an electrical generator. Through gearboxes, the generator converts the mechanical energy of the spinning turbine shaft into electricity. Electricity is now being generated on commercial scale at large installations called “wind farms” in several places around the world. Wind farms consist of rows of towers, sometimes 90 meters high, equipped with giant wind turbines for producing electricity.

The environmental impact of large wind turbines is negligible compared with an open pit coal mine or a reservoir and during their operation produce no air pollution.

Because of these factors, wind energy is recognized as the world’s fastest-growing new energy source. Small, highly efficient wind turbines are becoming popular as a source of electricity for rural homes [25].

Power is growing at the rate of 30% annually, with a worldwide installed capacity of 157,900 megawatts (MW) in 2009 [14]. It is widely used in Europe, Asia, and the United States. The measured wind speeds can be analyzed and the annual mean value can be calculated. If the yearly mean wind velocity is averaged over various years, areas of similar wind speeds can be identified. Figure 10: shows these values on a worldwide scale referring to 10 m above ground.

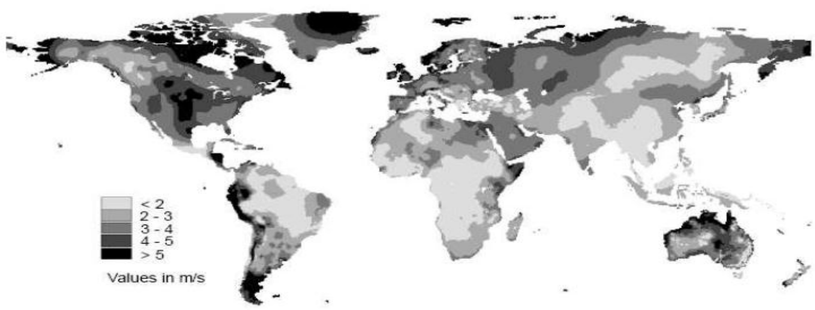


Figure 10 Distribution of yearly annual mean values of the wind speed for 10 m above ground worldwide [15].

Most modern wind energy converters are equipped with rotors to extract wind power, and consist of one or several rotor blades. The extracted wind power generates rotation and is thereby converted into mechanical power at the rotor shaft.

Mechanical power is taken up at the shaft in the form of a moment at a certain rotation and is transferred to a machine (such as a generator). The entire wind power station thus consists of a wind energy converter (rotor), a mechanical gear and a generator. It is physically impossible to technically exploit the entire wind energy, as in this case air flow would come to a standstill; air would fail to enter the swept rotor area, and wind power would no longer be available[16].

2.9. Seasonal and latitude variation in Ethiopia

Seasonal and daily variation in wind velocity is also considerable; wind velocity is higher between early morning and mid-day and in terms of seasonal variation, in the highland plateau zone there are two peak seasons – March to May and September to November; and in the eastern lowlands wind velocity reaches its maximum between May and August. In most of these places, maximum wind velocities are 3 to 4 times greater than the minimum. Medium to high wind speed of 3.5 to 6 m/s exists in most Eastern parts and central Rift Valley areas of the country. Perhaps due to their mountainous terrain and land use/land-cover type, most western and north-western parts of the country have generally low wind velocity.

Wind energy is considered a promising complementation to hydropower, since the two resources unfold their potential anti-cyclic: in rainy seasons the hydropower potential is high whereas low winds prevail. Vice versa hydropower potential is low in the dry season whereas the wind potential is high [26].

2.10. Component of wind energy system

A wind-energy system, which consists of most or all of these components:

• Loads in a system are energy-using devices, such as lights, appliances, and other electricity users.

• A tower supports a wind generator, getting it up into the smooth, strong wind that's needed to generate meaningful amounts of electricity.

•Transmission wiring and conduit allow you to transfer energy from where it's made to where it's stored and used.

• Wind generators (or turbines) collect the energy in the wind and use it to make electricity [25].

2.11. Wind Turbine

The wind energy system transforms the kinetic energy of the wind into mechanical or electrical energy that can be harnessed for practical use. Mechanical energy is most commonly used for pumping water in rural or remote locations, the "farm windmill" still seen in many rural areas of the U.S. as a mechanical wind pumper, but it can also be used for many other purposes as grinding grain, sawing, pushing a sailboat, etc. [8].

The wind turbines are classified as the horizontal axis wind turbine and the vertical axis wind turbine based upon whether the axis of rotation is parallel or perpendicular to the ground [13].

2.11.1 Horizontal Axis Wind Turbine (HAWT)

Today the HAWT is the most cost-effective means of capturing wind energy. They are positioned on land or at sea in a proven windy area. Most horizontal axis turbines are built with two or three blades.

HAWTs have the main rotor shaft and electrical generator at the top of a tower, and must be face the wind. Small turbines are pointed by a simple wind vane, while large turbines generally use a wind sensor coupled with a servo motor. It most have a gearbox, which turns the low rotation of the blades into a quicker rotation that is more suitable to drive a generator, this can be seen in figure 11

A wind farm is used to generate electricity in bulk. Several wind turbines, grouped together, form a wind farm. The electrical power that is generated from the turbines is distributed to customers from a utility grid. The utility grid works much in the same way as a conventional power plant [9].

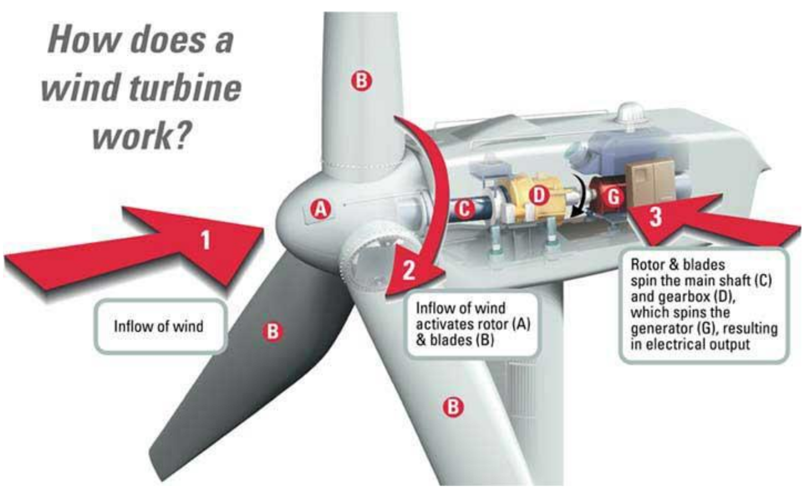


Figure 11 Internal turbine diagram (left) and HAWT (right)

2.11.2 Vertical Axis Wind Turbine (VAWT)

Vertical axis wind turbines are different from traditional wind turbines in that their main axis is perpendicular to the ground. Their configuration makes them ideal for both rural and urban settings and offers the owner an opportunity to offset the rising cost of electricity and to preserve the environment.

Besides, they do not need the complicated head mechanisms of conventional horizontal axis turbines.

- VAWTs in addition to being simpler and cheaper to build have the following advantages:
- VAWTs are not affected by the direction of the wind which is useful in areas where the wind changes direction frequently or quickly.
- VAWTs are better able to harvest turbulent air flow found around buildings and other obstacles. This situation is more common in areas where people live.
- VAWTs are ideal for both rural and urban applications including roof top installations.
- The generator or other devices can be installed at the ground level, making it simpler to install or maintain.
- VAWTs do not kill birds and wild life, it is because the slow moving and highly visible.
- VAWTs can be significantly less expensive to build.
- They produce less noise compare with horizontal ones.
- VAWTs are more esthetically pleasing.

The first aerodynamic vertical axis wind turbine was invented by Georges Darrieus in France and first patented in 1927. The common Darrieus rotor has two or three blades; they have shaped like an egg-beater. In the past the Darrieus rotor has been tested in different dimensions. In fact, one of the largest turbines ever built was the 96m high 64m diameter and it is located in Quebec, Canada. Another version of the Darrieus Wind Turbines is the, also called H-rotor. The main difference from the egg-beater shape is the straight aerodynamic profiles. Other VAWT configurations include the Savonius, which is popular because of the simplicity of manufacture, and the straight Bladed VAWT. All these turbines can be observed in figure 12

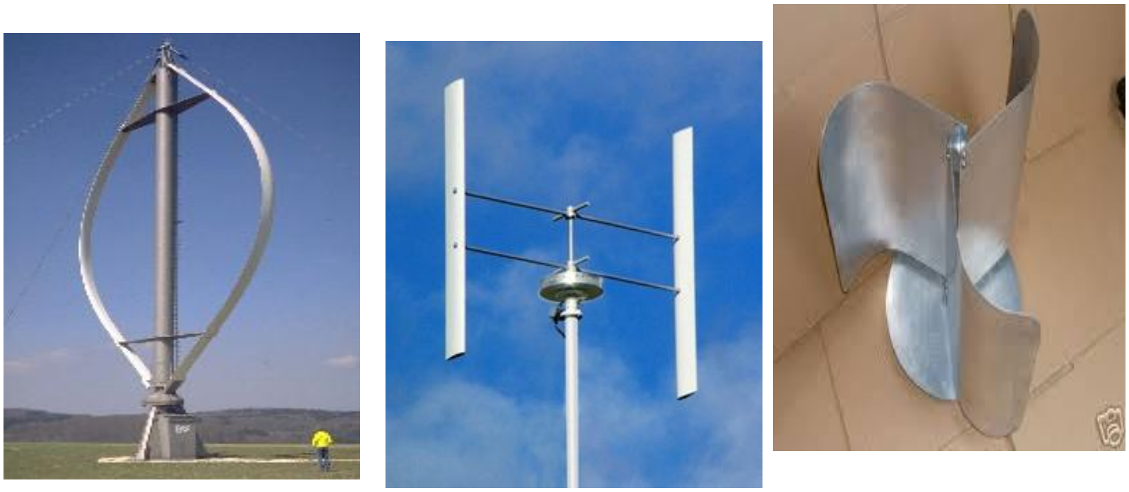


Figure 12 Darrieus Wind turbine (left), H-rotor (center) and Savonius (right)

There are two main types of VAWTs:

1. Darrieus turbines
2. Savonius turbines

VAWTs allow the mounting of equipment at ground level, unlike HAWTs which eases access and reduces cost. However, they are generally less efficient than traditional HAWTs. Improvements in blade design and the introduction of control mechanisms to allow the rotor speed to vary with wind speed have increased their efficiency.

2.11.2.1 Darrieus VAWT

In 1931 a French engineer called George J. M Darrieus invented a new type of VAWT. Its principle of operation depends on the fact that its blade speed is a multiple of the wind speed, resulting in an apparent wind throughout the whole revolution coming in as a head wind with only a limited variation in angle. They are lift type machines which tend to run very fast.

The Darrieus turbine [5] consists of two or more aero foil blades attached to the top and bottom of a rotating vertical shaft. These could be straight, giving the machine an "H"-shaped profile, but in practice most machines have the curved "egg-beater" or troposkien profile. The main reason for this shape is because the centrifugal force caused by rotation would tend to bend straight blades, but the skipping rope or troposkien shape taken up by the curved blades can resist the bending forces effectively. The wind blowing over the aero foil contours of the blade creates an aerodynamic lift and actually pulls the blades along.

Figure 13 The Darrieus VAWT [5]

A symmetrical aero foil isn’t the most efficient approach in providing lift. A design goal was to maximize lift at the same time as utilizing the inevitable drag created by the opposing blade. The wind flowing over the high lift and low drag blade profile, coupled with the blade areas’ solidity gives the machine the initial power to overcome its inertia. Once momentum has been established the forward movement of the blade through the air creates its own local wind flow over its contours creating a varying amount of lift throughout the full 360° of its rotation. In its downwind stroke, the curved underside of the blade acts like the sail of a yacht therefore creating usable torque throughout its rotation.

The stalling of the blades at the top and bottom of their arc rotation is also useful as it regulates the speed of the blades rotation, implying that the blades accelerate up to a point of equilibrium at which they won’t increase their speed no matter how hard the wind blows.

In comparison with the “drag-type” Savonius turbines, Darrieus type turbines offer higher efficiency since they reduce the losses due to friction. However, they are incapable of self-starting 20 since independently of wind they have a very low starting torque. They therefore require an auxiliary device to start, such as a motor or use in combination with a Savonius turbine. For the combined type Darrieus-Savonius, the starting torque is represented by the Savonius turbine coaxial and internal to the Darrieus turbine.

Figure 14 Combined Darrieus-Savonius [5]

A subtype of Darrieus turbine with straight, as opposed to curved, blades is known as the Giromill or Cycloturbine. The Cycloturbine variety has variable pitch to reduce the torque pulsation and is self-starting. The advantages of variable pitch are: high starting torque; a wide, relatively flat torque curve; a lower blade speed ratio; a higher coefficient of performance; more efficient operation in turbulent winds; and a lower blade speed ratio which lowers blade bending stresses. Straight, V, or curved blades may be used.

The main characteristics of the Darrieus-type turbine are:

- "Fast" turbine
- Reduced efficiency in comparison with horizontal axis turbines, also because a great part of the blade surface rotates very close to the axis at a low speed
- Adaptability to variations in the direction of the wind
- Effective for winds with an important vertical component of speed (sites on slopes or installation on the roof of the buildings "corner effect")
- Suitable for low values of wind speed and for a limited range

- ❖ Necessity of an adequate speed control to keep the efficiency within acceptable values
- ❖ Impossibility of reducing the aerodynamic surface in case of speed exceeding the rated one because of the fixed blades
- ❖ Necessity of a mechanical break for stopping the turbine
- ❖ Necessity of a structure not extremely robust to withstand extreme winds (given the smaller surface of the blades exposed to the wind in comparison with Savonius turbines)
- ❖ Suitable for large power applications
- ❖ Low noise and with vibrations limited to the foundations, therefore suitable to be installed on buildings
- ❖ Able to operate also under turbulent wind conditions gearbox and electric generator may be positioned at ground level
- ❖ High fluctuations of the motive mechanical torque.

2.11.2.2 Savonius turbine

The Savonius turbine is a vertical axis machine which uses a rotor that was introduced by a Finnish Engineer, S. J. Savonius in 1922 [5]. In its simplest form it is two cups or half drums fixed onto a central shaft in opposing directions. Each cup/drum catches the wind and so turns the shaft, bringing the opposing cup/drum into the flow of the wind. The cup/drum then repeats the process causing the shaft to rotate further and completing a full rotation. This process continues all the time the wind blows and the turning of the shaft is used to drive a pump or small generator.

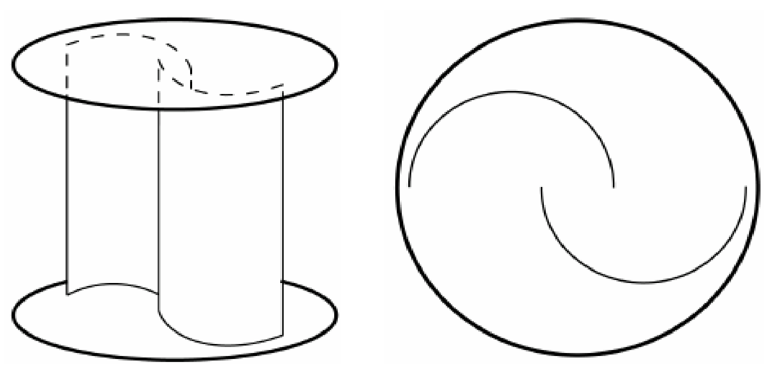


Figure 15 Savonius Turbine [12]

The Savonius rotor is simple in structure and has good starting characteristics, relatively low operating speeds and an ability to accept wind from any direction. It has a lower aerodynamic efficiency compared to the Darrieus and H-rotor.

Savonius claimed a maximum coefficient of power of 0.31. However field trials done by him on the Savonius rotors gave a maximum coefficient of 0.37. However the same hasn't been achieved by subsequent researchers. this means that the main driving force is drag force of wind acting on its blade. However at low angles of attack, lift force also contributes to torque production. Hence Savonius rotor is not a purely drag machine but a compound machine.

Although conventional Savonius rotors have low aerodynamic efficiency, they have a high starting torque or high coefficient of static torque. Due to this they can be used as starters for other types of wind turbines that have lower starting torques and for applications that require high starting torque such as water pumping.

When turning, the Savonius rotor presents the wind with a concave and convex section, and derives most of its power from drag. The drag coefficient for a flow perpendicular to the convex face of half a drum/pipe is 1.2 while the drag coefficient for the concave section is nearly twice as high at 2.3. Therefore the force on the concave side of the rotor is higher inducing a torque that turns the rotor. In addition to the torque due to the drag flow through the gap between the two rotor blades causes lift with thrust out the back face of the rotor helping it turn in the desired direction. Drag based rotors generally have a higher starting torque but lower efficiency when compared to modern lift based rotors.

The main characteristics of Savonius turbine are:

- “Slow” turbine
- Low efficiency value
- Suitability for low values of wind speed and within a limited range
- Necessity of adequate speed control to keep the efficiency within acceptable values
- Impossibility of reducing the aerodynamic surface in case of speed exceeding the rated one because of the fixed blades
- Necessity of a mechanical break for stopping the turbine
- Necessity of a robust structure to withstand extreme winds (the high exposed surface of the blades)

- Suitable for small power applications only
- High starting torque
- Low noise.

These characteristics make the Savonius turbine particularly suited for applications such as a source of power for water supply & irrigation in rural areas. The Darrieus turbine on the other hand, whilst having high efficiency and tip speed ratios exceeding unity, needs to be coupled to a generator that converts its high speed into electric power which in turn runs a pump. This increases the cost of the installation as well as its complexity. The high starting torque also makes the Savonius turbine suited to matching to applications with reciprocating pumps which require three times as much torque to start them as compared to that used to run them. (Source http://www.types of vertical axis wind turbine.

2.12. Estimation of electricity demand in Ethiopia

99% of households, 70% of industries and 94% of service enterprises use biomass as energy source. Households account for 88% of total energy consumption, industry 4%, transport 3% and services and others 5%. The installed electricity generating capacity in Ethiopia is about 2060 MW (88% hydro, 11% diesel and 1% thermal) and production covers only about 10% of national energy demand. The country is completely reliant on imports to meet its petroleum requirements.

According to the World Bank only an estimated 12% of the Ethiopian population has access to electricity. With almost 85% of the Ethiopians living in rural areas, there is a significant bias between the power supply of urban and rural population: only 2% of the rural but 86% of the urban residents has access to electricity. The overloading of the network frequently disrupts the power supply of large commercial and industrial customers. There is a need for substantial investments in the power system. [26]

Analysis made on historical sales and GDP data for the period 1973 to 2007 reveals that the electricity demand has an elasticity of 2.15 to changes in the overall GDP.

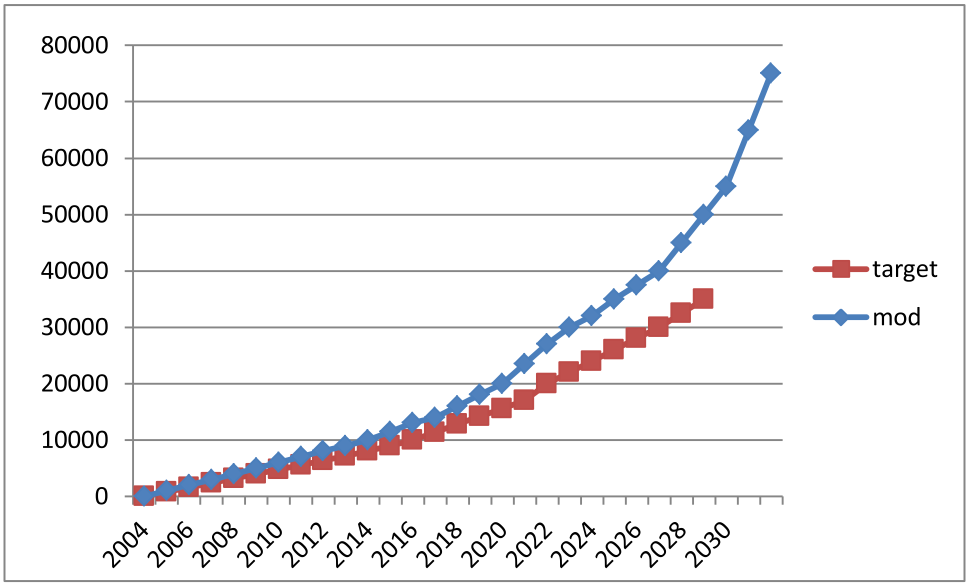


Figure 16 EEPCo's electrical power demand forecast

If an economic growth rate of 7-10% can be achieved in the coming years, It could be translated to an electric energy demand growth rate of about 17% (as projected in the target scenario) based on the above elasticity estimate [28].

2.13. Wind Energy in Ethiopia

Ethiopia has good wind resources with velocities ranging from 7 to 9 m/s. Its wind energy potential is estimated to be 10,000 MW. The Ethiopian National Meteorological Services Agency (NMSA) began work on wind data collection in 1971 using some 39 recording stations located in selected locations. Ever since the establishment of these stations, wind velocity is measured and data made available to consumers. However, the number of stations established, quality of data (in terms of comprehensiveness) and the distribution of the stations leaves much to be desired. On the basis of data obtained from existing wind measurement stations two important conclusions can be drawn:

•First and foremost, Ethiopia's wind energy potential is considerable.

•Secondly, wind energy is highly variable over the terrain mainly as a function of topography of the country. Pockets of areas with high wind velocities of up to 10 m/s are distributed throughout the Eastern half of the country, including the western escarpment of the Rift Valley. [26]

Generally EEPCo in its recent nationwide effort to enhance its energy production has so far spotted 7 promising wind farm sites with an approximated potential of over 760 MW power to be installed by 2013 (Wind Fair, 2010; EPA, 2010). While the Ashegoda project is the first wind farm in the country and believed to be the largest wind farm in Africa, EEPCo has signed another agreement with a German company to install a wind farm that is expected to generate some 60MW of electric power when completed by 2013 (Wind Energy PPP, 2010). The project execution is set to start by the end of 2010. Two projects at Adama and Mesobo Harena sites with a capacity of 51MW each have also been signed between EEPCo and Hydro China International in mid-2009 (Ibid.). Table 2 summarizes the different wind power projects that EEPCo has planned to install before 2013. Some of the projects are already underway.

Table 2 Ethiopian wind power projects scheduled to be executed before 2013

(Source: EPA, 2010)

No	Project	Generating capacity (MW)	Year of commissioning
1	Adama WPP	51	2011
2	Ashengoda WPP	120	2012
3	Ayisha WPP	300*	2012
4	Messobo WPP	42	2012
5	Adama II WPP	51	2013
6	Assela WPP	100	2013
7	Debre Birhan WPP	100	2013
Total		764	

* The Wind Energy PPP report put this figure to only 60MW

A successful completion of the 7 wind farm projects tabulated above alone would increase the nation’s current installed capacity of about 1,843MW (approximated from the available 11 hydropower plants, excluding diesel and geothermal) by more than 40%. However, the installation activity of the wind farms is feared to be jeopardized by poor transportation infrastructure. For instance, the feasibility study of the Ashegoda and Mesobo-Harena projects found out that transportation of the turbines is a major obstacle in both projects (GTZ, 2006a; GTZ, 2006b). Consequently, both studies have underlined the fact that it would take several months to transport the turbines from the port of Djibouti to the final sites due to lack of adequate transport infrastructure and a detailed transportation concept is recommended to be dealt with prior to the actual execution of both projects (GTZ, 2006a; GTZ, 2006b). In fact, the extent of this problem could be minimized by using many small sized turbines with a capacity of less than 1MW. Wiese et al. (2009), for instance, gave the ongoing Ethiopian Ashegoda wind farm project, where 120 units of 1MW turbines are being used, as a prime example of the implementation of larger wind parks with smaller-capacity turbines in areas where there is poor infrastructure. However, the problem with these types of turbines is that they need more space for the wind farm. But some potential areas, for instance Mesobo-Harena, have site limit restrictions on the space available [27].

3. METHODS AND MATERIALS

The task begins with the selection of the most feasible design in terms of fulfilling the stated objectives. This is already done by selecting Savonius type rotor invented by S .J. Savonius profile b/c of its simplicity in design and its satisfactory high efficiency. As is shown on the table below, it is observed that the recent wind speed data is obtained have a five year average wind speed 4.34m/s at 10m height. Accordingly, a wind speed of 4.34m/s is selected as a design wind speed but Savonius rotor works even below this average wind speed at tower heights less than 10m.

The work is conducted according to the following general procedure

- Design Savonius vertical axis wind turbine.
- Development of cad model of Savonius vertical axis wind turbine.
- Constructing prototype of wind turbine.
- Demonstrate the electricity generation from local wind.

3.1 Project site

According to the data we got from the national meteorology agency Adama branch, the wind energy is good enough for generating electricity. The table below shows five year average wind speed on a month

Table 3 Average wind speed in m/s per each month for 5 years at 10m

Month	YEARS				
	2010	2011	2012	2013	2014
Jan	4.774194	5.006452	3.032258	4.76129	4.787097
Fe	2.890323	3.470968	4.587097	4.76129	3.896774
Mar	3.548387	3.787097	5.348387	3.793548	4.419355
Apr	3.064516	3.56129	5.316129	3.096774	4.064516
May	2.883871	3.883871	5.051613	4.219355	4.148387
Jun	4.032258	9.535484	3.375484	5.258065	4.729032
Jul	2.864516	3.477419	4.56129	4.909677	4.96129
Aug	3.63871	3.322581	8	4.529032	4.212903
Sep	5.445161	2.645806	4.890323	3.870968	2.993548
Oct	4.141935	4.870968	5.530968	3.529032	3.96129
Nov	2.851613	3.845161	5.019355	4.606452	4.987097
Dec	3.96129	5.070968	5.070968	4.651613	4.916129
AWSPY	3.674731	4.373172	4.981989	4.332258	4.339785

According to the data listed above our group is proposing to select a Savonius vertical axis wind turbine to utilize the lower wind speed. Because HAWT is not functional throughout the year. This requires above 3.5 m/s to operate. For example the number written bold indicates that the HAWT will not be functional.

Table 4 Five year average wind speed (m/s)

Month	YEARS				
	2010	2011	2012	2013	2014
Jan	4.774194	5.006452	**3.032258**	4.76129	4.787097
Fe	**2.890323**	3.470968	4.587097	4.76129	3.896774
Mar	3.548387	3.787097	5.348387	3.793548	4.419355
Apr	**3.064516**	3.56129	5.316129	**3.096774**	4.064516
May	**2.883871**	3.883871	5.051613	4.219355	4.148387
Jun	4.032258	9.535484	**3.375484**	5.258065	4.729032
Jul	**2.864516**	3.477419	4.56129	4.909677	4.96129
Aug	3.63871	**3.322581**	8	4.529032	4.212903
Sep	5.445161	**2.645806**	4.890323	3.870968	**2.993548**
Oct	4.141935	4.870968	5.530968	3.529032	3.96129
Nov	**2.851613**	3.845161	5.019355	4.606452	4.987097
Dec	3.96129	5.070968	5.070968	4.651613	4.916129
AWSPY	3.674731	4.373172	4.981989	4.332258	4.339785

3.2. Wind energy availability

People think that as long as they can feel the wind, sufficient electricity should be generated from the wind turbine. They have often dreamed of a small wind turbine that can be installed on the roof of a house can provide all the energy they need. However, this is not the case. We should learn more on the limits of wind. Like anything in nature, there are limits to what is possible.

The power that is available in the wind depends on the wind speed, the density of the wind (which varies with altitude and temperature), and the amount of turbulence (swirling) in the wind. Wind speed is high up in the sky and low at the ground level. You may notice that you are difficult to fly a kite at the ground. However, when the kite is flied up in the sky, you will feel the high wind force.

The power available at a given wind speed passing through an area (e.g. a window) can be calculated by using the following formula:

$$P = \frac{1}{2} \cdot \rho \cdot A \cdot v^3 \quad (5)$$

Where:

P is power in Watt (W).

ρ is the density of air in Kilograms per cubic meter (Kg/m^3)..

A is the cross section area of the wind passing through in sq. meter (m^2).

v is the velocity of the wind in meters per second (m/s).

The density of air at sea level and room temperature is approximately 1.3 Kg/m^3.

The available power from the wind increases dramatically with the swept area but so do the stresses on the blades. The swept area is the area the windmill's blades cover during a rotation.

The power depends on the cube of the velocity. This means that when the wind speed doubles, the available power is increased by a factor of 8. In other words, when the wind speed reduces in half, the available power reduced to 1/8 of the original value. There is very little available power below 11 Km/h, but as wind speed increases the power becomes very significant.

Turbulence and Drag are always associated with wind. They cause rapid variation of pressure and velocity in space and time.

They detract our ability to extract mechanical energy from the wind. In general, wind turbines are typically installed as far above ground level obstacles as possible, since trees and buildings add to turbulence.

In order to have an idea of how much energy is available in the wind, we can refer to the Beaufort scale. At wind speed of 11 Km/h or less, we can only felt the wind on our exposed skin. Thus, there is only limited wind energy under 11 Km/h [22].

3.3 parameters that are considered during project implementation

3.3.1 Output power

There are many complicated calculations and equations involved in understanding and constructing wind turbine generators however the layman need not worry about most of these and should instead ensure they remember the following vital information:

1) The power output of a wind generator is proportional to the area swept by the rotor - i.e. double the swept area and the power output will also double.

2) The power output of a wind generator is proportional to the cube of the wind speed - i.e. double the wind speed and the power output will increase by a factor of eight (2 x 2 x 2)!

3. 3.2. Power coefficient

Power coefficient, (Cp) of a wind turbine is the ratio of maximum power obtained from the wind to the total power available in the wind [19]. This hypothesis shows the relationship between the power coefficient (Cp) and the wind speed (V), which expresses the basic theory of the Savonius wind turbine. Principally the power that the Savonius rotor can extract from the wind (Pw) is less than the actual available from the wind power (Pa). The available power (Pa), which is also the kinetic energy (KE) of the wind, can be defined as:

$$KE = Pa = \frac{1}{2} m_a . v^2 \qquad Pa = \frac{1}{2} \rho . As . V^3 \tag{6}$$

Where:

Ma = wind mass flow rate striking the swept area of the wind turbine (kg/sec). = ρ. As. V

But, the swept area (As = H * D), therefore the actual power becomes:

$$Pa = \frac{1}{2} \rho . H . D . V^3 \tag{7}$$

The power that the rotor extracts from the wind is: $\boldsymbol{Pw} = \boldsymbol{T} * \boldsymbol{\omega}$ (Watt) (8)

Where:

Pw = the power that the rotor extracts from the wind (Watt).

The power coefficient (Cp) is given by:

$$\mathrm{Cp} = \frac{\text{the extracted power from the wind}}{\text{the avaliable power of the wind}} = \frac{\mathrm{Pw}}{\mathrm{Pa}} \tag{9}$$

3.3.3. Swept area

As the rotor turns, its blades generate an imaginary surface whose projection on a vertical plane to wind direction is called the swept area [9]. The amount of energy produced by a wind turbine primarily depends on the rotor area, also referred to as cross-sectional area, swept area, or intercept area. The swept area for Savonius wind turbine can be calculated from the dimensions of the rotor (Figure 17).

Savonius area = the swept area = As = H * D (10)

Where: H = the rotor height (m).

D = the rotor diameter (m).

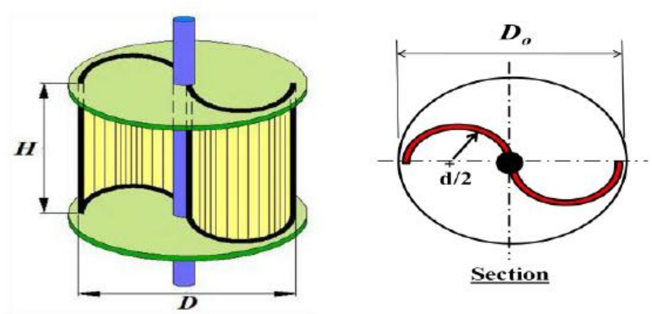


Figure 17 Schematic diagram of Savonius rotor wind turbine

3.3.4. Wind speed

This is very important to the productivity of a windmill. The wind turbine only generates power with the wind. The wind rotates the axis (horizontal or vertical) and causes the shaft on the generator to sweep past the magnetic coils creating an electric current. If the wind speed increases the power of the wind to produce electricity increases and vice versa.

3.4.5. The Tip speed ratio (TSR):

The tip speed ratio is the ratio of the product of blade radius and angular speed of the rotor to the wind velocity [19]. The tip peripheral velocity of the rotor (Vrotor) is defined as (Figure:18):

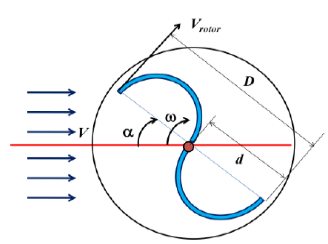


Figure 18 Scheme of a Savonius rotor showing the tip velocity of the rotor

$\boldsymbol{V_{rotor}} = \boldsymbol{\omega * d}$ (11)

Where: V_{rotor} = the tip speed (the peripheral velocity of Savonius rotor) (m/sec)

ω = the angular velocity of Savonius rotor (rad/sec).

d = the diameter of the semi-cylindrical Savonius rotor (m).

Now the Tip Speed Ratio (TSR) of a turbine is expressed as:

$$\text{The tip speed ratio (TSR)} = \lambda = \frac{\text{Vrotor}}{\text{V}} = \frac{\omega * \text{d}}{\text{V}} \qquad (12)$$

Where: V = the wind speed (m/sec)

3.3.6. Tower height

Wind velocities increase at higher altitudes due to surface aerodynamic drag (by land or water surfaces) and the viscosity of the air. The variation in velocity with altitude, called wind shear, is most dramatic near the surface. Typically, the variation follows the wind profile power law, which predicts that wind speed rises proportionally to the seventh root of altitude. Doubling the altitude of a turbine, then, increases the expected wind speeds by 10% and the expected power by 34%. To avoid buckling, doubling the tower height generally requires doubling the diameter of the tower as well, increasing the amount of material by a factor of at least four [19].

3.3.7. Chord length

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

3.3.8. The Torque Coefficient (Ct):

It is defined as the ratio between the actual torque developed by the rotor (T) and the theoretical torque available in the wind (Tw) [19], thus the torque coefficient (Ct) is given by:

$$\text{Ct} = \frac{\text{the rotor torque}}{\text{the wind torque}} = \frac{\text{T}}{\text{Tw}} = \frac{\text{T}}{\frac{1}{4} * \rho * \text{As} * \text{d} * \text{V}^2} \qquad (13)$$

Where:

Ct = the torque coefficient

T = the rotor torque (N. m)

Tw = the wind available torque (N. m)

ρ = the air density (kg/m^3)

Another concept that can be used to measure the wind turbine performance is the static torque (Ts), which measures the self-starting capability of the turbine. Static torque is defined as a maximum value of the torque when rotor is blocked i.e. without ability to rotate [19]. So, the static torque coefficient is given by:

$$\mathrm{Cts} = \frac{\mathrm{Ts}}{\mathrm{Tw}} = \frac{\mathrm{Ts}}{\frac{1}{4} * \rho * \mathrm{As} * \mathrm{d} * \mathrm{V}^2} \quad (14)$$

Where:

Cts = the static torque coefficient

Ts = the rotor static torque (N . m)

3.3.9. Angular velocity

Increasing the angular velocity of the rotor/ turbine /generator increases the output power and vice versa.

3.3.10 Solidity

Is usually defined as the percentage of the circumference of the rotor which contains material rather than air, Savonius is a high solidity machine. It generates much higher starting torque than low-solidity machines, like Darrieus for example, Another advantage of high-solidity machines is that they do not need to be made with as much precision as low-solidity ones. This type of turbine is self-starting and provides high torque at low speeds.

3.3.11. Aspect ratio

This is one of the parameters that are used in describing blade configuration of the rotor. It is defined by the ratio of height of the rotor to its diameter. It is an influential factor in determining the optimum blade configuration for a particular blade profile. Power output for a given cross-sectional area of the rotor varies significantly with a variation of aspect ratio. [20].

3.3.12. Base Height

The height of the base affects the windmill immensely. The higher a windmill is, the more productive it will be due to the fact that as the altitude increases so does the wind speed.

3.3.13. Blade Length

This is important because the length of the blade is directly proportional to the swept area. Larger blades have a greater swept area and thus catch more wind with each revolution. Because of this, they may also have more torque.

3.3.14. Blade end gap and overlap

Blade gap describes the gap between the two blades; and is defined by the length of the horizontal line normal to the surface of the two overlap blades. And blade overlap refers to length of the extension of one blade towards the opposite blade; and is defined by the distance between the inner edges of the two overlap blades. R. Gupta, et al done the CFD analysis of a rotating two-bucket Savonius rotor with 0 rotor angle for five overlaps, namely 16.2%, 20%, 25%, 30% & 35% was carried out using Fluent 6.3.26 software. Velocity and static pressure contours were generated for each overlap condition and then these were analyzed Static pressure decreases from upstream to downstream side of the rotor. The maximum pressure drop is found in case of 16.2% overlap (18.41e+02 Pa) and minimum in case of 35% overlap (9.27e+02 Pa) meaning maximum power extraction from wind by the rotor at 16.2% overlap condition. The net pressure on the advancing and returning buckets comes out to be almost equal in case of 16.2% overlap (about 1.02e+03 Pa), which would ensure stability of the rotor at 16.2% overlap by minimizing vibration during rotation [35].

3.4. Uses for prototype design

To provide a purpose for building this prototype, other than results obtained from natural wind testing, the device was considered for more practical purposes. The limiting factor is the power output of 2.5 kilo watts generated in a 6.51m/s wind flow, which therefore makes this turbine only suitable for medium applications by utilizing straight away and storing. These are listed below.

- ✓ For emergency aid electric demand on highway away from town.
- ✓ Low-power applications such as individual domestic installations.
- ✓ Automotive battery charging in rural areas

3.5. Materials used to construct the project

Introduction to Materials Selection

Materials were selected by considering the materials' properties that can withstand the environmental conditions as well as the cost.

Materials usage in Savonius wind turbine

A wide range of materials are used in wind turbines. There are substantial differences between small and large machines and there are projected changes in designs that will accommodate the introduction of new material technologies and manufacturing methods. To arrive at a total, the material usage is weighted by the estimated market share of the various manufacturers and machines types. In general the materials used for wind turbines are Steel, Aluminum, Copper and Reinforced Plastic

In this project we have used Aluminum sheet metal and aluminum sheets. The following are certain important properties present in the materials selected.

Table 5 Machine parts selected criteria

No	Machine parts	Selected materials	Selected criteria
1	Shaft	Solid steel bar	b/c it is less in thickness & light in weight
2	Rotor blade	Aluminium sheet	For easy self-starting
3	pully	Aluminium	b/c it has less in weight
4	Base	Steel bar	For prevention of collapsing
5	Permanent magnet	Car alternator	b/c there is high output
6	Tower	Steel bar	b/c it helps to increase the tower stability
7	End plate	Aluminium sheet	Due to its light in weight corrosion, résistance, rigidity, & it is easy to construct & low cost

3.6 Electrical circuit diagram of the system

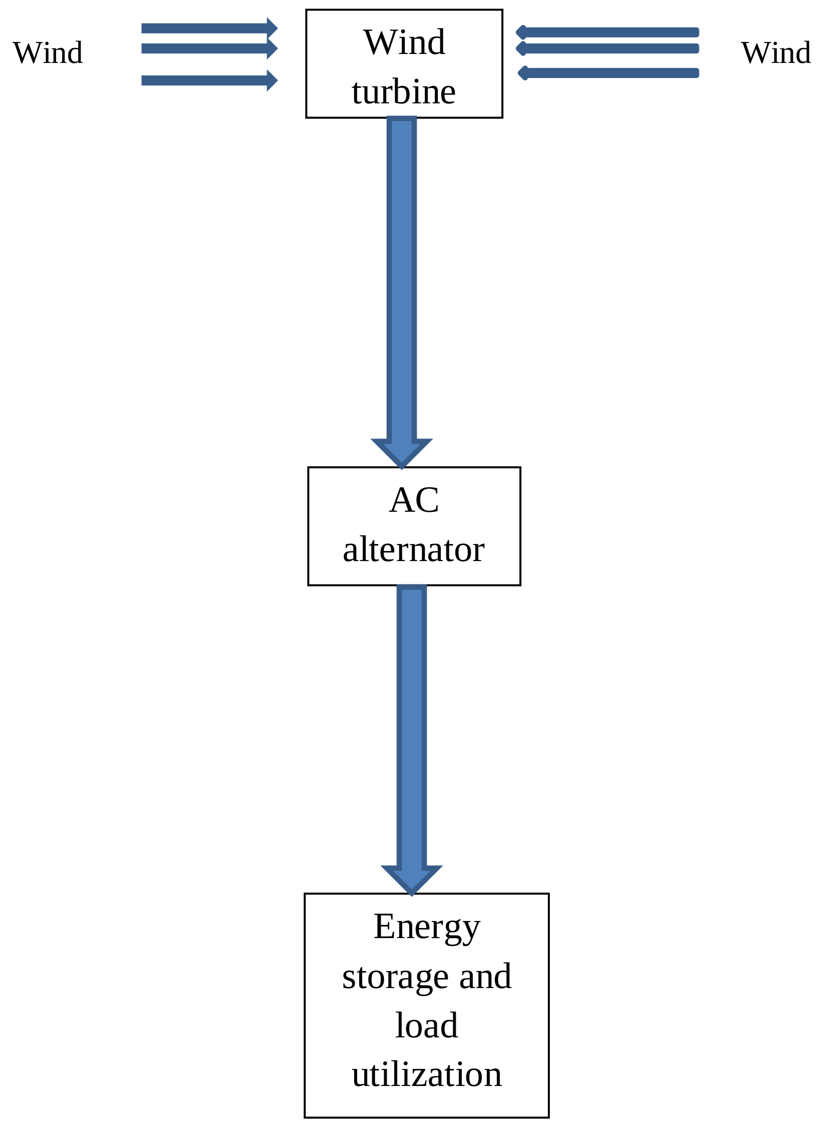


Figure 19 Electric flow circuit diagram of VAWT

3.7. Methodology

This project relates to design and development of Savonius vertical axis wind turbine for generating electricity using local wind channeling the induced wind in the direction of the wind turbine. The kinetic energy of the wind movement thus created can be used to generate electricity.

The following schematic diagram shows the steps involved in the project.

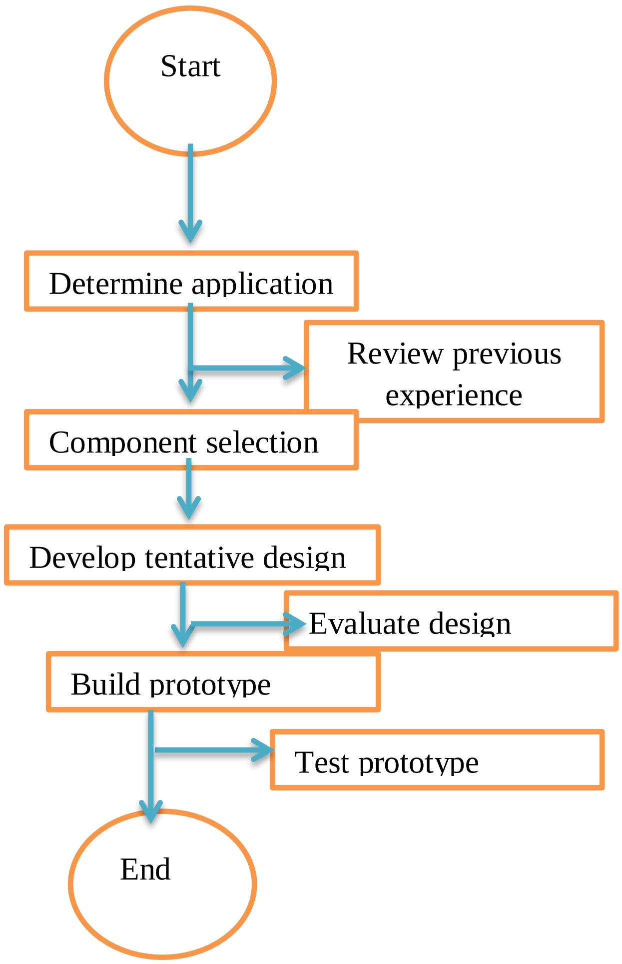


Figure 20: The steps involved in development of small scale Savonius wind turbine

3.8. Basic design and calculation of the project components

3.8.1. System layout

A wind mill is a machine for wind energy conversion. A wind turbine converts the kinetic energy of the wind's motion to mechanical energy transmitted by the shaft. A generator further converts it to electrical energy. So it is necessary to keep in mind, while designing the windmill's structural part.

3.8.2 Theory and calculating dimensions

Wind power, Pw is defined as the multiplication of mass flow rate, ρAV and the kinetic energy per unit mass, ½ V^2. The wind power is denoted by the equation of:

$$Pw = \frac{1}{2} \rho A V^3 \qquad (15)$$

The swept area for Savonius wind turbine is calculated by multiplication of rotor diameter, D and the rotor height, H. The larger the swept area, the larger the power generated.

$$A = D.H \qquad (16)$$

3.8.3. Efficiency of Wind Turbine

Wind turbine efficiency is quantified by a non-dimensional value called the coefficient of power C_P, which is the ratio of power extracted from the wind, P, to the total power in wind crossing the turbine area. Equation (17) shows that the coefficient of power is a function of the air density ρ, the area inscribed by the turbine blade A, and the wind speed V_1 [30].

$$C_p = \frac{P}{\frac{1}{2} * \rho * A * v_1{}^3} \qquad (17)$$

The power extracted from the wind is derived using the Bernoulli equation on both sides of a wind turbine as described in Figure 21.

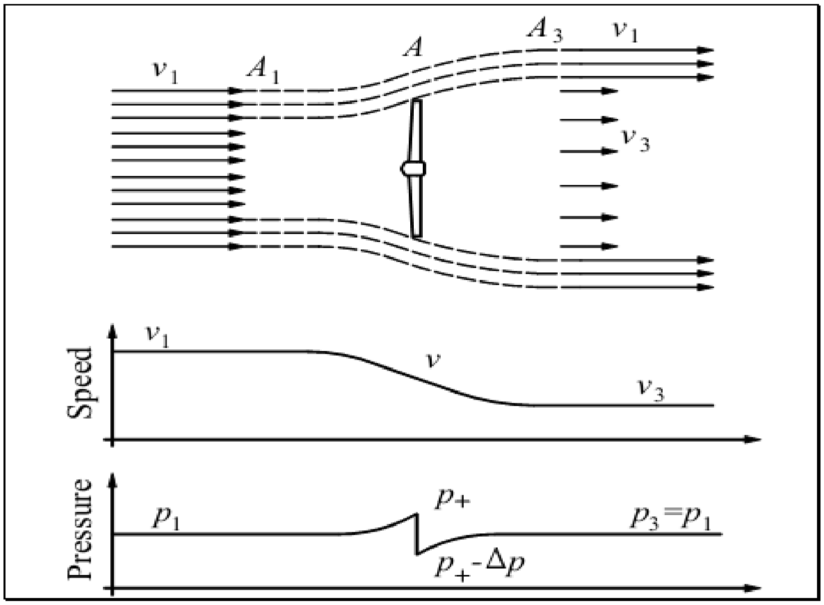


Figure 21: Diagram of Wind Speed and Pressure Before, During, and After Crossing a Wind Turbine [30]

By applying the Bernoulli equation to the flow upstream and downstream of the turbine results in Equation (18) and (19), respectively.

$$p_1 + \frac{1}{2\rho v_1^2} = p_+ + \frac{1}{2}\rho\, v^2 \quad (18)$$

$$p_+ - \Delta p + \frac{1}{2}\rho\, v^2 = p_1 + \frac{1}{2}\rho\, v_3^2 \quad (19)$$

By subtracting Equations (18) and (19), one arrives at the following expression:

$$\Delta p = \frac{1}{2}\rho(v_1^2 - v_3^2) \quad (20)$$

Based on the change in linear momentum from v_1 to v_3, the change in pressure Δp can also be expressed as:

$$\Delta p = \rho\, v(v_1 - v_3) \quad (21)$$

By solving equations (20) and (21) for v,

$$v = 1/2(v_1 + v_3) \quad (22)$$

The power produced by the wind turbine is equal to the kinetic energy in the air.

$$P = 1/2\rho v(v_1^2 - v_3^2) \quad (23)$$

The axial interference factor a is a factor that represents the loss in wind speed as it approaches the turbine blade. The axial interference factor is defined as:

$$v = (1 - a)v_1 \tag{24}$$

Or
$$v_3 = (1 - 2a)v_1 \tag{25}$$

In terms of the axial interference factor, the power equation from Equation (23) can be re-written as:

$$P = 2\rho a(1 - a)^2 v_1^3 A \tag{26}$$

Using Equation (26) to further define the power extracted by the wind turbine in Equation (17), the coefficient of power can be defined in terms of the axial interference factor only.

$$C_P = 4a(1 - a)^2 \tag{27}$$

The maximum theoretical value of the coefficient of performance is determined by setting the derivative of Equation (27) equal to zero and solving for a. Doing so results in a root at a =1/3, which corresponds to a maximum coefficient of power of 16/27. This number, referred to as the Betz limit, represents the maximum theoretical coefficient of power.

According to the Betz limit, there is at most only 59.3 % of the wind power can be converted into useful power. Some of the energy may lose in gearbox, bearings, generator, transmission and others. The maximum power coefficient, Cp for Savonius rotor is 0.30 [31]. Hence, the Cp value used in this project is 0.30 and the power output, P with considering the power efficiency is:

$$P = 0.15\ \rho A V^3 \tag{28}$$

This power coefficient only considers the mechanical energy converted directly from wind energy; it does not consider the mechanical-into-electrical energy conversion, which involves other parameters like the generator efficiency.

Wind speed is the major element that affects the power output. The three wind speed parameters involve in this project is cut-in speed, rated wind speed and cut-out speed. the three wind speed parameters related to the power performance are as follow [31].

$$V_{\text{cut-in}} = 0.5V_{\text{ave}} \tag{29}$$

$$V_{\text{Rated}} = 1.5V_{\text{ave}} \tag{30}$$

$$V_{\text{cut-out}} = 3.0V_{\text{ave}} \tag{31}$$

All these parameters depend on the value of average wind speed. The average wind speed V_{avg} was found 4.34m/s by taking the data from the metrology agency of Adama town. Table 6 summarizes the value of these three wind speed parameters.

Table 6 Value of cut-in speed, rated wind speed, and cut-out speed.

Wind Speed Parameter	Equation	Calculation
Cut-in speed, Vcut-in	Vcut-in = 0.5 Vavg	2.17 m/s
Rated wind speed, VRated	VRated = 1.5 Vavg	6.51m/s
Cut-out speed, Vcut-out	Vcut-out = 3 Vavg	13.02 m/s

Aspect ratio is a crucial criterion to evaluate the aerodynamic performance of Savonius rotor. The Savonius rotor is designed with rotor height twice of rotor diameter and this lead to better stability with proper efficiencies [31].

$$AR = H/D \tag{32}$$

Tip speed ratio, λ is defined as the ratio of the linear speed of rotor blade ω.R to the undisturbed wind speed, V. ω is the angular velocity and R represents the radius revolving part of the turbine. The maximum tip speed ratio that Savonius rotor can reach is 1. Write that high tip speed ratio improves the performance of wind turbine and this could be obtained by increasing the rotational rate of the rotor.

$$\lambda = \omega.R / V \tag{33}$$

Solidity is related to tip speed ratio. A high tip speed ratio will result in a low solidity. Solidity is defined as the ratio of blade area to the turbine rotor swept area.

For VAWT, the solidity is defined as

$$\sigma = n\, d / R \tag{34}$$

Where n is the number of blades, d is the chord length or can be defined as the diameter of each half cylinder, and R is radius of wind turbine. Many researchers have proved that the higher the number of blades, the higher the performance of most wind turbine. However, some researchers found that the two-bladed Savonius rotor has higher performance than three-bladed Savonius rotor [31]. Referring to researchers then the two-blade rotor has been chosen for this project.

3.8.4. Transmission and generator efficiencies

The shaft power output that we have been discussing is not normally used directly, but is usually coupled to a load through a transmission or gear box. The load may be a pump, compressor, grinder, electrical generator, and so on. For purposes of illustration, we will consider the load to be an electrical generator. The basic system is then as shown in Fig. 22 We start with the power in the wind, Pw. After this power passes through the turbine, we have a mechanical power Pm at the turbine angular velocity $\dot{\omega}_m$, which is then supplied to the transmission. The transmission output power Pt is given by the product of the turbine output power Pm and the transmission efficiency η_m[32].

$$Pt = \eta_m P_m \qquad W \qquad (35)$$

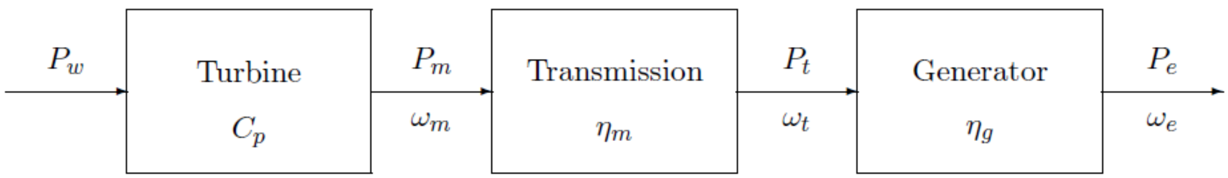


Figure 22: Major components of wind electric system [32]

Similarly, the generator output power Pe is given by the product of the transmission output power and the generator efficiency η_g:

$$P_e = \eta_g P_t \qquad (\text{W}) \qquad (36)$$

Equations 28, 35, and 36 can be condensed to a single equation relating electrical power output to wind power input:

$$P_e = C_P \eta_m \eta_g P_w \qquad (\text{W}) \qquad (37)$$

At rated wind speed, the rated electrical power output can be expressed as

$$P_{eR} = C_{pR} \eta_{mR} \eta_{gR} \frac{\rho A V_R^3}{2} \qquad (\text{W}) \qquad (38)$$

Where Cp_R is the coefficient of performance at the rated wind speed VR ,$\eta_m R$ is the transmission efficiency at rated power, $\eta_g R$ is the generator efficiency at rated power, ρ is the air density, and A is the turbine area.

The quantity $C_{pR} \eta_{mR} \eta_{gR}$ is the rated overall efficiency of the turbine. We shall give this quantity a symbol of its own, η_o: where

$$\eta_o = C_{pR} \eta_{mR} \eta_{gR} \qquad (39)$$

To estimate the power output of the system using equation (23), firstly, the total efficiency (η_o) need to be estimated. Taking a conservative estimation for (the rotor efficiency of 30%, [31]) generator efficiency around 90%, and transmission efficiency around 90%, we achieved a total efficiency of 24.3 % using equation (39). With the efficiency of the complete system and the estimation of the power output (2.5kw), the area of the rotor could be calculated made using Eq. (38).

$$P_{eR} = C_{pR}\eta_{mR}\eta_{gR}\frac{\rho A V_R^3}{2}$$

2.5 KW = 0.5 x 0.243 x 1.225 x A x $(6.51)^3$

2500 W = 41.06A

A = 2500/41.06

A = 60.88 m^2

The Savonius rotor is designed with rotor height twice of rotor diameter and this lead to better stability with proper efficiencies.

AR = H/D = 2

Therefore H = 2D

A = H X D = 2D X D = $2D^2$

60.88 m^2 = $2D^2$

D^2 = 30.44 m^2

D = $\sqrt{30.44\, m^2}$ = 5.517 m

H = 11.034 m

Note: - an end plate parameter (end plate diameter/rotor diameter) of 1.1 (recommended by Benesh [33]) will be used both model and prototype rotor in this project.

$D_{\text{end plate}}$ = 1.1 x 5.517m = 6.069 m

Table 7: Summary of design parameters

Parameter	Value
Power Generated	2.5kW
Swept Area	60.88m^2
V rated	6.51 m/sec
Aspect Ratio	2
Tip Speed Ratio	1.0
Solidity	2.114
Diameter – Height	5.517m – 11.034 m
Number of Blade	2

The design of the Savonius rotor blade is shown in Figure 23 while Table 7 shown the detail dimension of the Savonius rotor blade. The material proposed for the Savonius rotor blade in this paper is aluminium sheets. Since the manufacturing process and material cost considered in this paper, the material is chosen based on their properties.

Table 8 summarizes the general properties of the aluminium sheets and also rotor blade for this paper.

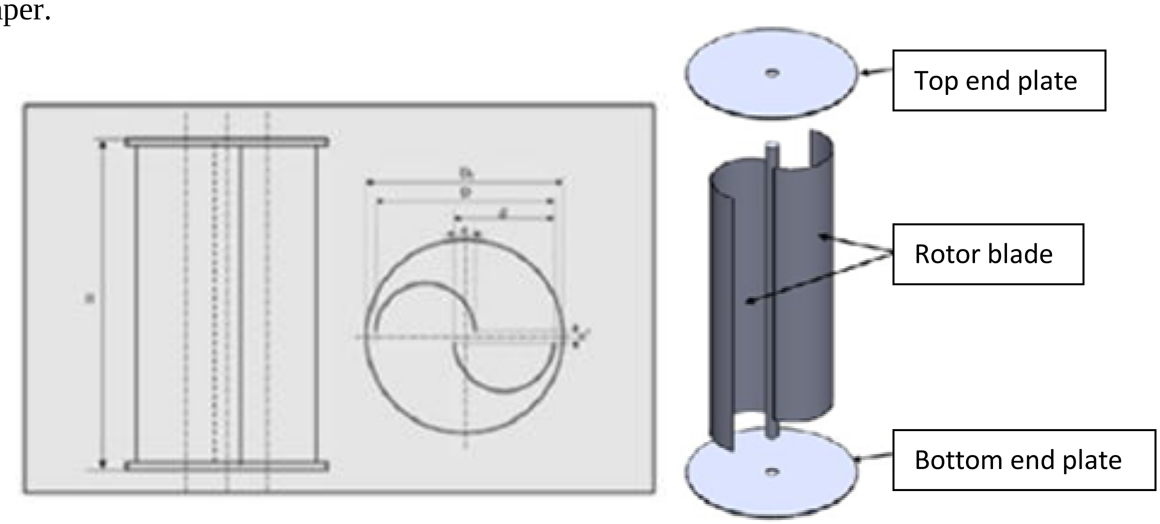


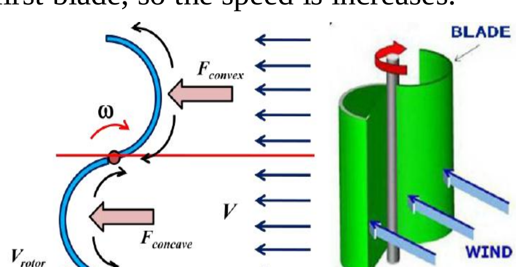
Figure 23: Design of Savonius rotors

Table 8 Summaries of rotor blade design and the material properties of aluminium sheet metals

Parameter	Value
Swept Area, A	60.88m^2
Rotor Diameter, D	5517mm
Rotor Height, H	11034 mm
End Plate Diameter, Df	6069 mm
Chord Length, d	2858.5 mm
Overlap Distance, e	200 mm
Blade Thickness, t	0.8 mm
End Plate Thickness, tf	1 mm
Density AL	2.7 M g/m3
Young’s modulus (AL)	70 G Pa
Poisson’s ratio (AL)	0.34
Tensile strength (AL)	70--700 Mpa
Compressive strength (AL)	276 – 460 Mpa

3.8.5.. Blade Dimension

Savonius wind turbine blades have S (two half circle) type shape. While designing the size of blade it is must to know the weight and cost of blades. In this project two blades made from aluminium sheet metal with vertical shaft made from aluminium bar are used, it has a height & diameter of 11034mm and 5517mm mm respectively and has a thickness of 0.8mm. The two blades have overlap. So if one Blade moves other blades comes in the position of first blade, so the speed is increases.



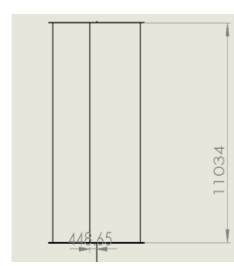


Figure 24: Calculated Savonius Blade dimension

3.8.6 Dimension of pulley and belt

Pulleys are used to transmit power from one shaft to another by means of belts.Since the velocity ratio is the inverse ratio of the diameters of driving and driven pulleys, therefore the pulley diameters should be carefully selected in order to have a desired velocity ratio.

The pulleys must be in perfect alignment in order to allow the belt to travel in a line normal to the pulley faces [36].

The basic data required for drive selection a following:

- Distance between axes of pulley (C)
- AC estimated electric power(P)
- Motor rotation speed (n_1).
- Output rotational speed (n_2)
- The service factor based on the type of driver and driven load.
- length of the belt (Lp)
- size of the smaller pulley(d)
- size of the large pulley(D)
- The correction factor for belt length.
- The correction factor for the angle of wrap on the smaller pulley
- The number of belts
- The initial tension on the belt

Two different diameters of pulleys with larger diameter on the rotor blade driver shaft and smaller driven diameter on the generator shaft is designed to increase the RPM of generator shafts to have continuing expected power output. For the case of this design, it is decided to have a velocity ratio of 1:10.

Now from the design concept selection small diameter of pulley and velocity ratio (Vr), it is possible to calculate the large pulley diameter on the wind turbine shaft.

$\text{Vr} = \frac{d}{D}$ Where, D – is diameter of larger pulley on the motor shaft;

d – is diameter of small pulley on the driven shaft;

$\frac{1}{2} = \frac{71\text{mm}}{\text{D}}$, D = 10x71 =710mm

So, select the following data from the standard table of appendix for the design purpose.

- Belt width of section A=13mm
- Belt thickness of section A=8mm

- Estimated power output of section A =3.35 HP
- Service Factor of section=1.8
- Minimum pulley pitch Diameter=71mm
- Large pulley diameter =710mm
- belt Center distance 1641.83mm

Now by taking a tip speed ratio 1 means the roto blade tip travels thruogh air at the same speed as the wind. Therefore the rotor RPM is calculated as follows.

$$\text{RPM} = \frac{(V \times 60)\times \lambda}{\pi \times D} = \frac{(6.51\times 60)\times 1}{3.142\times 5.571} = 22.32 \text{ rpm}$$

This rpm is also the pulley. Because the pulley directly connected to the rotor througn a fixed shaft. So by taking 22.32 RPM on larger pulley(on the driving shaft), the rpm of the smaller pulley (on the driven shaft) to estmate the ratio of n_2 is given by:-

$dxn_1 = Dxn_2$,where n_2 – is rpm of smaller pulley

n_1- is rpm of larger pulley

$$\frac{n_2}{D} = \frac{n_1}{d}, \quad n_2 = \frac{n_1 \times D}{d} \qquad n_2 = \frac{22.32rpm \times 710mm}{71mm} = 223.2 \text{ rpm}$$

For any type of the belt drive it is always desirable to know the length of belt required. It will be required in the selection of the belt. The length can be determined by the geometric considerations. However, actual length is slightly shorter than the theoretically determined value.

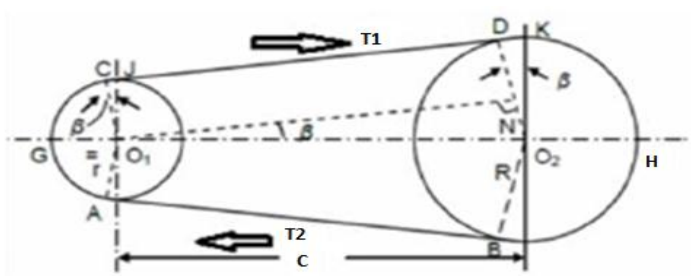


Figure 25: Belt drives (From Engineering Data book for v – belt.)

The belt of A-shape is chosen.

Formula for a recommended distance of axis or center distance is given by:

$\frac{D+d}{2} + 50 <= A <= \left(2 \times (D + d)\right)$

$= \frac{710+71}{2} + 50 <= A <= 2 \times (710 + 71) = 390.5 <= A <= 1562$

so,for the design A is chosen ~ **1562mm**

Determine the V-belt Length.

from the belt drive shown on figure 3.9, Angle of a slope of the belt is calculated as follow,

By geometry, $< O_2 O_1 N = < C O_1 J = < DO_2 K = \beta$

Arc BHD = $(\pi + 2\beta)$ R, and

Arc CGA = $(\pi + 2\beta)$r

AB = CD = $O_1N = O_1 O_2 \cos\beta = A \cos\beta$

Sin β = (D - d)/ c = (710-71)/1562 = 0.409091

$\beta = \text{Sin}^{-1}(0.409091) = 24.15^0$

Then length of the belt is calculated as follow,

$$\mathrm{L} = 2\mathrm{C} + 1.57(\mathrm{D} + \mathrm{d}) + \frac{(D-d)^2}{4C}$$

Where:

L = Pitch Length of Belt

C = Center Distance

D = Datum or Pitch Diameter of Large pulley

d = Datum or Pitch Diameter of Small pulley

β= be the angle subtended by the tangents AB and CD with $O_1 O_2$.

$L = (2 \times 1562) + 1.57(710 + 71) + \frac{(710-71)^2}{(4\times1562)}$ =3124+1226.17+65.35

=**<u>4415.52 mm</u>**

From the standard table of appendix 5, A it is close to the datum length of A180=4572mm Therefore, belt specification for this machine is A180; L4572mm V-belt is selected based on the appendix 4. These data are suitable and ISO standard because it describes the relations of center distance, pulley diameters and belt dimentions.in addition, it guides to select standard sizes and appropriate movements.

Calculate the exact center distance of the pulleys after the belt length has been determined.

$$C = \frac{b+\sqrt{b^2-2(Dp-dp)^2}}{4}$$

Where: b= Lp - 1.57(Dp + dp)

=4572mm-1.57(710+71)

= 3345.83mm

$$C = \frac{\mathbf{3345.83}+\sqrt{(\mathbf{3345.83})^2-2(710-71)^2}}{4}$$

=**1641.83mm**

Angle of contact of belt on each pulley

The angles are important because commercially available belts rated with on assumed contact angle of 180^0.this will occur only if the drive ratio is 1:1(no speed change).the angle of contact on the smaller of the two pulleys will always less than 180^0, requiring a lower power rating.

The tensile force in the belt maximum on the tight side of the belt. The bending of the belt around the pulley, maximum at the tight side of the belt bends around the smaller pulley.

$< AGC = \theta_1=180^0-2\sin^{-1}[\frac{D-d}{2c}]$

$<BHD = \theta_2=180^0+2\sin^{-1}[\frac{D-d}{2c}]$

Where θ_1= contact angle of belt on small pulley

Θ_2 = contact angle of belt on large pulley

L =Belt lengthss

C= center distance between pulleys

d = small pulley diameter

D = large pulley diameter

Contact angle of small pulley (θ1)

$$\theta_1 = 180 - 2\sin^{-}1\left[\frac{D-d}{2C}\right]$$

$$\theta_1 = 180 - 2\sin^{-}1\left[\frac{710-71}{2x1562}\right]$$

θ_1 = **156.39^o**

Contact angle of larger pulley (θ_2)

$$\theta_2 = 180 + 2\sin^{-}1\left[\frac{D-d}{2C}\right]$$

$$\theta_2 = 180 + 2\sin^{-}1\left[\frac{710-71}{2x1562}\right]$$

θ_2 = **203.61^0**

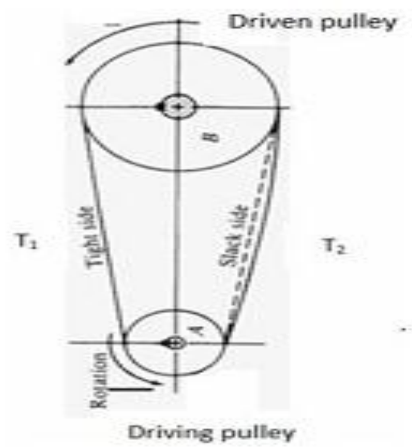
Tension in the belt

P= (T_1-T_2) V, Where T_1- is tension on the tight side of belt

T_2 – is tension on the slack side of belt

V – is velocity of the belt in small pulley.

P – is power from the above design = 302.4W



That is $V = \frac{\pi dN}{60,000}$

$$V = \frac{\pi \times 71 \times 223.2}{60,000}$$

$$V = 0.829 m/s$$

There fore $T_1 - T_2 = \frac{P}{V}$

$$T_1 - T_2 = \frac{302.4}{0.829}$$

= **364.78N**

Figure 26: Schematic showing the Belt tension side and the slack side

$2.3\log\left(\frac{T1}{T2}\right) = \mu\theta$ Where, μ - is Coefficient of friction between the smaller pulley and

V- Belt by taking μ = 0.12 from table.

θ- is contact angle on small pulley in radian that is 156.39^O

=2.74rad

$$\mathrm{Log}\left(\frac{T1}{T2}\right) = \frac{0.12x2.74}{2.3} = 0.143$$

$\frac{T_1}{T_2}$ =1.32 by taking anti log of 0.143

T1 = $1.32T_2$

Therefore by combining the two equations, that is

$1.32T_2$-T_2 =364.78N T_2 = 364.78N /0.32 = 1139.93 N in the slack side

T_1=$1.32T_2$ T_1=1.32 x 1139.93 = 124.68 N in the tight side

3.8.7. Shaft Dimension

Shaft is the component of a mechanical device that transmits rotational motion and power. To know that power transmitted (in watts) by the shaft

A pulley is pulled by belt tension on two sides. The tensions on tight and slack sides of belt, called T_1 and T_2 are related as $\frac{T_1}{T_2} = e^{\mu\theta}$ where μ is coefficient of friction between pulley surface and belt and θ is angle of contact between belt and pulley (figure 3.11). This figure is representing the simplest case in which two belt sides are vertical, θ being π. The shaft will be subjected to load T1 + T2 acting transversely [37]..

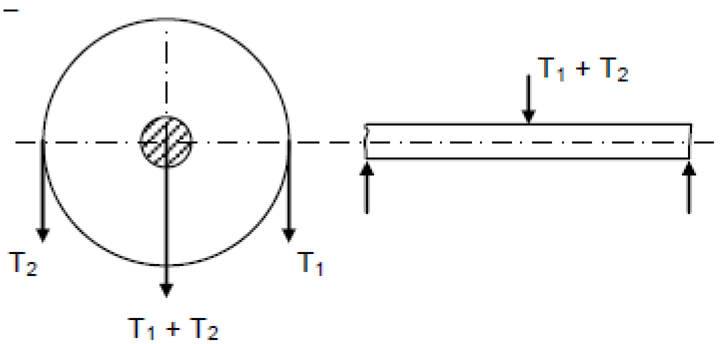


Figure 27: Loading of Shaft by Pulley [37]

Additionally the weight of pulley will also act at the same section. If the center line of T_1 and T_2 is inclined then components in vertical and horizontal planes can be found and bending moment in vertical plane is calculated by combining weight of the pulley with vertical component of the tension (T_1 + T_2). BM in horizontal plane is separately calculated and BM in horizontal and vertical planes is combined, thereafter. The torque on shaft is calculated as $(T_1 + T_2)\frac{D}{2}$ where D is the diameter of pulley.

$$Torque(T) = (T_1 + T_2)\frac{D}{2}$$

$$= \frac{(12439.68+9424)0.71}{2} = \mathbf{7761.6\ Nm}$$

Then twisting moment is obtained by: $T = \frac{Px60}{2\pi n}$

Where T- is twisting moment in N-m

n- Speed of shaft in RPM = 22.32RPM= 0.372 revolution per second

p- Power transmitted by shaft

$$P = \frac{2T\pi N}{60} = \frac{2\times7761.6\times\pi\times0.372rps}{60} = 302.4 \text{ W}$$

The shafts may be designed on the basis of

1. Strength, and
2. Rigidity and stiffness.

Designing shafts on the basis of strength

(a) Shafts subjected to twisting moment or torque only,

(b) Shafts subjected to bending moment only,

(c) Shafts subjected to combined twisting and bending moments, and

(d) Shafts subjected to axial loads in addition to combined torsional and bending loads.

The material used for ordinary shafts is carbon steel of grades 40C8, 45C8, 50C4 and 50 C12.

Table 9 Mechanical properties of steels used for shafts [36]

Indian standard designation	Ultimate tensile strength, MPa	Yield strength, Mpa	Remark
40c8	560-670	320	Used for shafts, gears stud bolts, spd le,washer etc. for light stressed
45c8	610-700	350	Used for lead screws, feed rods bige rgears, bigger shafts etc…
50c4	640-760	370	
50c12	700 Minimum	390	

From this mechanical properties of steels used for shaft, we choose 40c8 materials because our project is derived from simple mechanism by considering its yield strength of **320MP**a

The stress included in the shaft is:

- Shear stress due to transition of torque(due to torsional load)
- Bending stress (compression) due to force acting up on the shaft.
- Stress due to combined torsional and bending loads

Maximum permissible working stress for transition shafts

According ASME code for shaft purchased under definite physical specification, the permissible shear stress (allowable shear stress) is 25% of yield strength but not over 18% of ultimate strength in tension for shafts with key ways

τ=0.25σ_y or τ = 0.18σ_u where, τ = permissible shear stress

σ_y =yield strength

σ_u = ultimate tensile strength

Permissible shear stress is τ=0.25 x σ_y =0.25 x 320=**80MPa**.

Shafts Subjected to Twisting Moment Only

In this case, then the diameter of the shaft may be obtained by using the torsion equation.

We know, from the Text book of Machine design:

$\frac{T}{J} + \frac{\tau}{r}$ Where, T = Twisting moment (or torque) acting upon the shaft,

J = Polar moment of inertia of the shaft about the axis of rotation,

τ =Torsional shear stress, and

r = Distance from neutral axis to the outer most fiber = d /2;

We know that for round shaft, polar moment of inertia,

$$J= \frac{\pi}{32} X\ d^4$$

The equation may now be written as

$$\frac{T}{\frac{\pi}{32} \times\ d^4} + \frac{\tau}{\frac{d}{2}} \text{ or } T = \frac{\pi}{16} \times \tau \times d^3$$

From this equation we can determine the diameter of the shaft (d) as;

$$d = 3\sqrt{\frac{16xT}{\pi\tau}}$$

$$d = \sqrt[3]{16 \times \frac{7761.6N.M}{\pi \times 80 \times 10^6 \frac{N}{m^2}}}$$

d=0.0791m = 79.1mm

From equivalent twisting moment equation we know that

Te = $\sqrt{M^2 + T^2} = \sqrt{(6.85)^2 + (7761.6)^2}$ = **7761.61 N-m**

M=6.85 Nm from bending moment diagram

The equivalent twisting moment is given by

$$Te = \frac{\pi}{16}\tau d^3$$

Where

τ = is permissible stress =***80*** *MPa* for shaft diameter (d) to be dimensioned.

By re-arranging this equation yields d^3=16Te/πτ

$D = \sqrt[3]{\frac{16Te}{\pi\tau}} \quad = 3\sqrt{\frac{16x7761.61NM}{\pi x80000000}}$ = 0.0791m =79.1mm

Therefore to have better strength, standard design specification and more safe, the driven shaft diameter d is designed by rounding off this value to **79.1mm**.

Shear force diagram (SFD) & bending moment diagram (BMD)

Step1. Reactions

(Working in KNm)

0 = +(21.86*0.322) -(FR*12)

FR= $\frac{7.039}{12} = 0.5865$ KN

$+ \quad \sum F_y \uparrow 0$

0 = FL-21.86 + 0.5865

FL= 21.86-0.5865=21.273 kN

Step2. SFD

Cut anywhere;

Add forces on left hand side(LHS)

(or RHS -whichever is easier).

Use positive S.F. = Upwards on LHS

Step 3. BMD

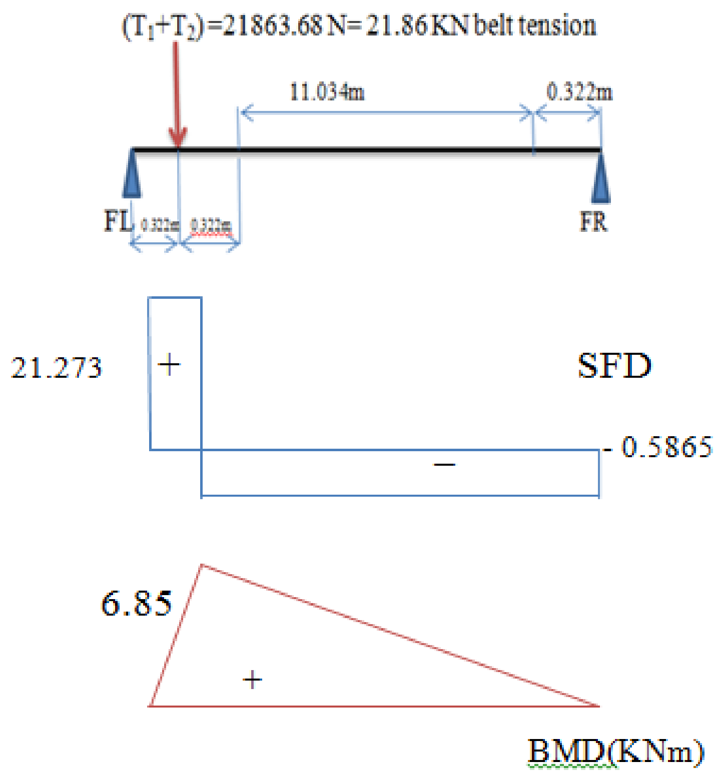


Figure 28: SF & BM diagram

Change of AREA of SFD = Change of height of BMD

(a) BM zero both ends (free ends)

(b) $0.322 \times 21.273 = 6.85$

(c) $11.678 \times -0.5865 = -6.85$

3.8.8. Selecting of Bearing

For the smooth operation of Shaft, bearing mechanism is used. To have very less friction loss the two ends of shaft are pivoted into the same dimension bearing. The Bearing has internal diameter of 79.1 mm. Bearing are generally provided for supporting the shaft and smooth operation of shaft. We have used ball bearings for the purpose of ease of maintenance & rotation.

3.8.9. End plate dimension

The rotor with end plates gives higher efficiency than those without end plates. The influence of radius Ro of these end plates relatively to the diameter R of the rotor has been experimentally studied [34]. the higher value of the power coefficient Cp is obtained for a value of Ro around 10% more than R, whatever is the velocity coefficient (Ro = 1.1R) [33]. The two end plates are designed from aluminium sheet metals of diameter 6068.7 mm and thickness of 1mm to obtain better performance. Both end plates and the two semi-cylindrical blades were assembled to a central shaft. Aluminum is the best choice due to its light weight, corrosion resistance, rigidity, recyclable materials, easy to construct and low cost.

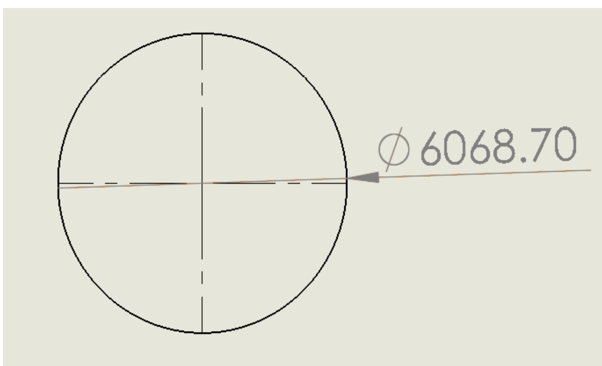


Figure 29: CAD drawing and picture of End-plate model

3.8.10. Tower /support dimension

The tower is constructed with dimensions of the height and width 13000 mm and 7000 mm respectively. The horizontal and vertical members of the tower, cut to the required sizes, are assembled by tying them with bolt and welding. A 7 m long horizontal steel bar is tied at the base of each stand, and their ends are tied to the top end of the rotor's stand with a guy cables. This helps in increasing the tower's stability.

3.9. CAD/CAM

Computer-aided design (CAD) is defined as the application of computers and graphics software to aid or enhance the product design from conceptualization to documentation. CAD is most commonly associated with the use of an interactive computer graphics system, referred to as a CAD system. Computer-aided design systems are powerful tools and in the mechanical design and geometric modeling of products and components.

There are several good reasons for using a CAD system to support the engineering design function:

- ✓ To increase the productivity
- ✓ To improve the quality of the design
- ✓ To uniform design standards
- ✓ To create a manufacturing data base
- ✓ To eliminate inaccuracies caused by hand-copying of drawings and inconsistency between drawings

Computer-aided manufacturing (CAM) is defined as the effective use computer technology in manufacturing planning and control. CAM is most closely associated with functions in manufacturing engineering, such as process and production planning, machining, scheduling, management, quality control, and numerical control (NC) part programming. Computer-aided design and computer-aided manufacturing are often combined CAD/CAM systems.

This combination allows the transfer of information from the design into the stage of planning for the manufacturing of a product, without the need to reenter the data on part geometry manually. The database developed during CAD is stored; then it is processed further, by CAM, into the necessary data and instructions for operating and controlling production machinery, material handling equipment, and automated testing and inspection for product quality.

For this project, CAD / CAM play an important role in the development of Savonius. In addition, by using Rapid Prototyping, each piece was printed [13].

3.10. Rapid Prototyping (RP)

Rapid Prototyping takes information from a three-dimensional (3D) computer-aided design (CAD) database and produces a solid model (prototype) of the design. The benefits of RP include:

- ✓ Reduced lead times to produce prototyped components
- ✓ Improved ability to visualize the part geometry due to its physical existence
- ✓ Earlier detection and reduction of design errors

- ✓ Increase capability to compute mass properties of components and assemblies

A number of RP technologies such as stereo lithography, selective laser sintering, fused deposition modeling, and 3D printing are available for producing plastic parts directly from design data created in any one of many commercially available CAD systems. Each part in this project was created by Strategy's dimension RP machine.

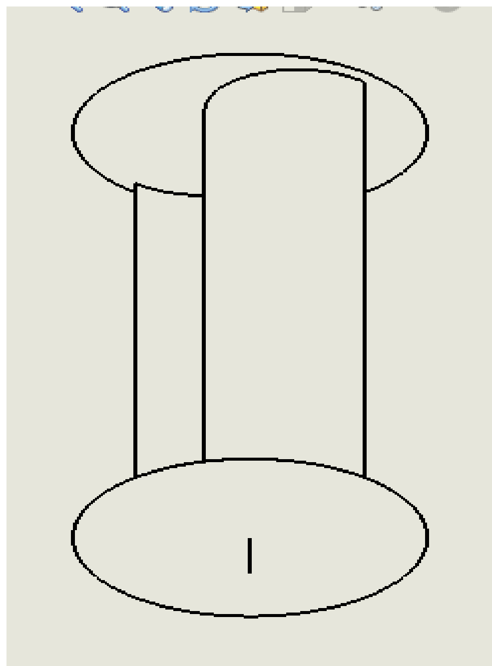


Figure 30: Cad model of Savonius wind turbine

3.11. Fabrication techniques

The following were the fabrication techniques involved

Materials Selection and Purchase

Materials were selected by considering the materials' properties that can withstand the environmental conditions as well as the cost.

3.11.1. Sheet metal cutting

Safety Precautions!

Utility knives and scissors can be dangerous! Use caution when cutting materials using them. The blades of most utility knives can be extended and locked in place. Extend the blades only far enough to cut all the way through the material, no farther. Be sure they are locked in position while cutting. ! Hot glue guns can cause serious burns, as can the glue if it comes in contact with your skin. ! The magnets you will be using can cause serious damage to computers or other electronic devices. Be sure to keep them away from credit cards, computer disks, audio tapes, or any other materials on which information is stored magnetically.

3.11.2. Gas welding

Gas welding, also called oxy-fuel welding, is a system of welding that uses one of various gases and oxygen to ignite a torch. Welding is defined as the process of combining two materials, usually metal, by heating them until both ends become molten. Filler materials are generally added into this molten material and the two ends are joined together and allowed to cool, forming one solid piece.

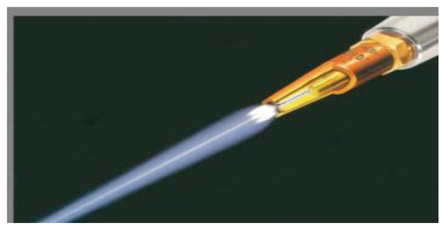


Figure 31 Gas welding torch

3.11.3. Arc welding

Arc welding uses a welding power supply to create an electric arc between an electrode and the base material to melt the metals at the welding point. They can use either direct (DC) or alternating (AC) current, and consumable or non-consumable electrodes. The welding region is sometimes protected by some type of inert or semi-inert gas, known as a shielding gas, and/or an evaporating filler material.

The process of arc welding is widely used because of its low capital and running costs The following gauge lengths of electrodes are used in this process 8, 10 &12mm. The number of electrodes used in this fabrication is around 40-45 electrodes.

Figure 32: Arc welding equipment

3.11.4. Riveting

A rivet is a permanent mechanical fastener. Before being installed a rivet consists of a smooth cylindrical shaft with a head on one end. The end opposite the head is called the buck-tail. On installation the rivet is placed in a punched or pre-drilled hole, and the tail is upset, or bucked (i.e. deformed), so that it expands to about 1.5 times the original shaft diameter, holding the rivet in place. To distinguish between the two ends of the rivet, the original head is called the factory head and the deformed end is called the shop head or buck-tail. Because there is effectively a head on each end of an installed rivet, it can support tension loads (loads parallel to the axis of the shaft); however, it is much more capable of supporting shear loads (loads perpendicular to the axis of the shaft). Bolts and screws are better suited for tension applications

Figure 33: Riveting equipment

Figure 34: Development of a prototype

Assembly

Assembling and installation; Fitting the rotor blades to other wind turbine components (transmission system, and tower) will be done next and basic performance assessment of the turbine will be finally done. The picture below is the complete rotor blade undergoing lab test. The prototype is exposed to local wind for testing. Experimental data on the power generated is compared to theoretical data construction of prototype

Figure 35: Assembled prototype Savonius vertical axis wind turbine rotor

Testing of the prototype was done in the lab using a wind tunnel as a source of wind

Figure 36: Testing the prototype using exhaust of the table top wind tunnel

3.12 Cost analysis

Economics is one of the most important aspects of any manufacturing operation. In order for the product to be successfully marketed, its cost must be competitive, optimum cost with similar product in the market place.

Availability and cost of raw materials and manufactured components are major concerns in persistent manufacturing. If raw or processed materials or manufactured components are not available in the desired quantities, shapes and dimensions, substitutes and/or additional processing will be required, which can contribute significantly to product cost For example,if we need a round bar of a certain diameter and it is not available in standard form, then we have to purchase a larger rod and reduce its diameter by some means ,such as machining, drawing through grinding.

The various cost components are involved in manufacturing a product, manufacturing manager has to identify those factors that can help to minimize them, while maintaining quality. These components are:-

- Raw materials cost.
- Operation processing cost.
- Consumable material and standard item cost.
- Overhead cost and
- Labor cost.

3.12.1 Raw material cost

The material and cost refers to those raw materials which are used to produce each components of Savonius wind turbine.

This analysis of cost estimation of the materials is carried on the basis of the data obtained from local markets Purchase documents of the faculty and Experience of market expertise.

Table 10 List of raw materials

Item number	Types of materials	Specification	Required size	Remark
1	Angle iron	1000mmx2000mmx1.5 mm	1000mmx1500mmx1.5mm	
2	Round bar	40mmx6000mmx3mm	40mmx1200mmx3mm	
3	Aluminium sheet metal	1000mm x 2000 mm x 0.8 mm	900mm x 1900mm x0.8mm	
4	Aluminium bar	Diameter 150 mm	Dia 140 mm	
5	Bearing	20 mm x 12 mm	20 mm x 12 mm	
6	Car alternator	Permanent magnetic	Electro magnetic	
7	Mild steel tubes	12 mm x 11 mm x 2000 mm	12 mm x 11 mm x 1300 mm	
8	Belt	v-belt	v-belt	

1. Aluminium sheet metals unit cost

   Standard size

   900mm x 1900 mm x 0.8 mm = 550 birr

   Required size

   900mm x 1900 mm x 0.8 mm x 1

   550 birr x 1 = **550 birr**

2. Bearing unit cost

   Standard size

   20 mm x 12 mm = 25 birr

   Require size

   20 mm x 12 mm x 3

   25 x 3 = **75 birr**

3. Aluminium bar unit cost

   Standard size

   Diameter 150 mm x 70mm (3kg) = 500 birr

   Required size

   Diameter 150 mm x 70mm (3kg) x 1

500 x 1 = **500 birr**

4. Mild steel Angle iron.

Standard size Unit cost

40 mm x 3 mm x 1500 mm = 400Birr

Required size

40mmx3mmx1500mm x 1

1x400 = **400Birr**

5. Mild steel square bar

Standard size Unit cost

Diameter 40mmx40mm 6000mm = 500 Birr

Required size

Dia 40 mm x 40 mm x 6000 mm x 1

500 x 1 = **500 birr**

6. Mild steel Tube bar.

Standard size Unit cost

Dia20mm x 20mm x 6000mm = 500Birr

Required size

Dia20mmx20mmx 8000 mm

6000mm = 500Birr

8000mm = ?

8000/6000 x 500 = **666.7 bir**r

7. Car alternator

Local = **700 birr**

8. V-Belt

A- type Diameter 500 mm = **45 birr**

The Total Raw materials cost is **= 3436.70 Birr**

3.12.2 Operation Processes cost

Many processes are used to produce parts and shapes, there is usually more than one method of manufacturing a part from a given material all methods have different process cost.

However Selection of a particular manufacturing process depends not only on the shape to be produced but also on a large number of other factors. The type of material and its properties are basic considerations. The design and cost of tooling, the lead time required to begin production and the effect of work piece materials on tool life are major considerations. Therefore the total operational time will be estimated as

1. rotor blade = 480 min
2. end plate = 360 min
3. shaft = 180 min
4. support / tower = 720 min
5. pulleys = 150 min
6. assembling = 720 min

   Total time = 2610 min

If Operation processing cost is 60Birr/ hour and the operational cost will be

60 x 2610min/60 = **2610 .00Birr**

3.12.3 Consumable material and standard item cost

Materials that are consumed during manufacturing the products beside the raw materials for this Savonius VAWT are:-

Table 11 Consumable material and standard item cost

		Standard type and size	Required number/size	Unit/packet /cost(Birr)	Total cost(Birr)
1	Hack-saw blade	Flex-Back 14/inch-Sweden	2	30	60
2	Electrode	E-1011 Dia 2.5	1	200	200
3	Grinder disc	Diameter 180 mm	1	50	50
4	Bolt and nut	M10x1.5mmx3mm	4	10	40
5	Thinner for paint	In liter	1	60	60
6	color paint	In liter	1	85	85
7	Brush for paints	In inch 3/4"	1	25	25
8	Sand paper	200mmx6000mm - No 120	1	100	100
				Total cost	620.00

3.12.4 Overhead cost

Overhead cost includes different expenses for the production processes it may be the cost for deprecation of the machine used, house rent, electric consumption, telephone, water, taxation and other costs. It is calculated easily by multiplying the percentage of the sum total raw material and consumable material cost. It depends of the standard or income of the country and varies from 15%to20% of the martial cost. So ones the raw material, consumable material and standard items cost are strictly calculated the sum total will be multiplied by the standard percentage.

Table 12 Overhead cost

raw material cost	3436.70
consumable material and standard item cost	620.00
Sum total of material cost	4056.7
overhead cost 15% x 4056.7	608.505

3.12.5 Labor cost

Labor costs are generally divided into direct and indirect costs**.** The direct labor cost is for labor directly involved in manufacturing the part (productive labor).This cost includes all labor from the time; materials are first handled to the time the product is finished. The direct labor cost is calculated by multiplying the labor rate (hourly wage, including benefits) by the time that the worker spends producing the part and wage of the market.

For example - If the Savonius VAWT will require 60hours

If the workers wage is 120birr per day and If the working time /day is 8 hour then

56 hour/8 = 7 days

Therefore the labor cost is = 7 days x120 Birr

= **840.00 Birr**

3.12.6 Total production cost of Savonius VAWT

It is clear that the total production cost of the machine is the sum of all the above mentioned cost that is:-

Table 13 Total production cost of Savonius VAWT

Raw materials cost	3436.70
Operation processing cost	2610.00
Consumable material and standard item cost	620.00
Overhead cost and	608.505
Labor cost.	840.00
Sub Total cost	**8115.205 ETB**
For market change (contingency) is 5%	405.76
Total	**8520.96 ETB**

4. Results and Discussion

For the different wind speeds tested, the rotor blade gave different RPM and voltage. Although the design wind speed for the turbine was 6.51 m/s, from the results the turbine's capacity to capture power at lower wind speeds was still considerable.

Table 1 gives the results of the electrical power output for different wind speeds while figures 37, 38, 39 and 40 gives the maximum electrical power output, current and voltage with RPM at different wind speeds.

Table 14 Maximum electrical power output at different wind speed

Wind speed (m/s)	Voltage (v)	Current (A)	Rotational speed (RPM)	Power output (W)
5	1.14	0.00	60	0.00
7	1.29	0.00	100	0.00
9	4.23	0.01	250	0.000423
11	5.26	0.1	310	0.0526

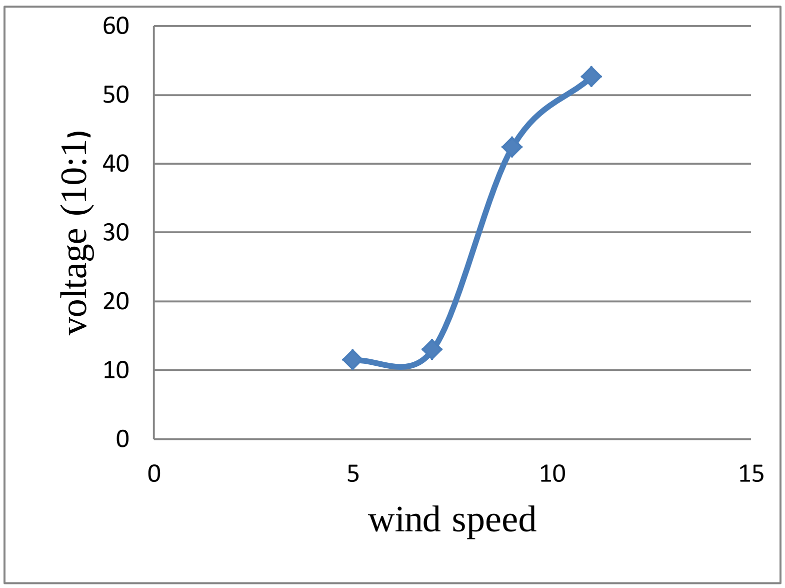


Figure 37: Maximum electrical voltage Vs wind speed

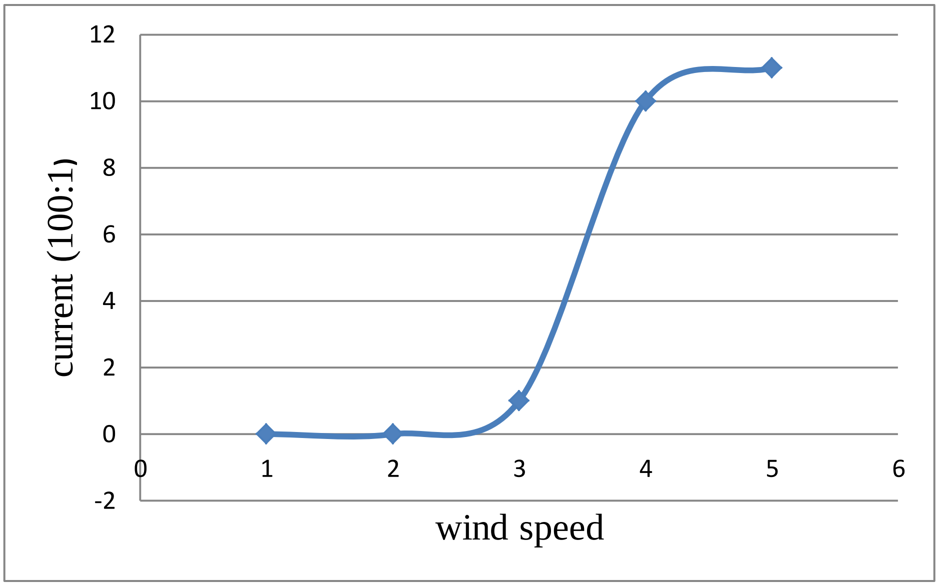


Figure 38: Maximum electrical current Vs wind speed

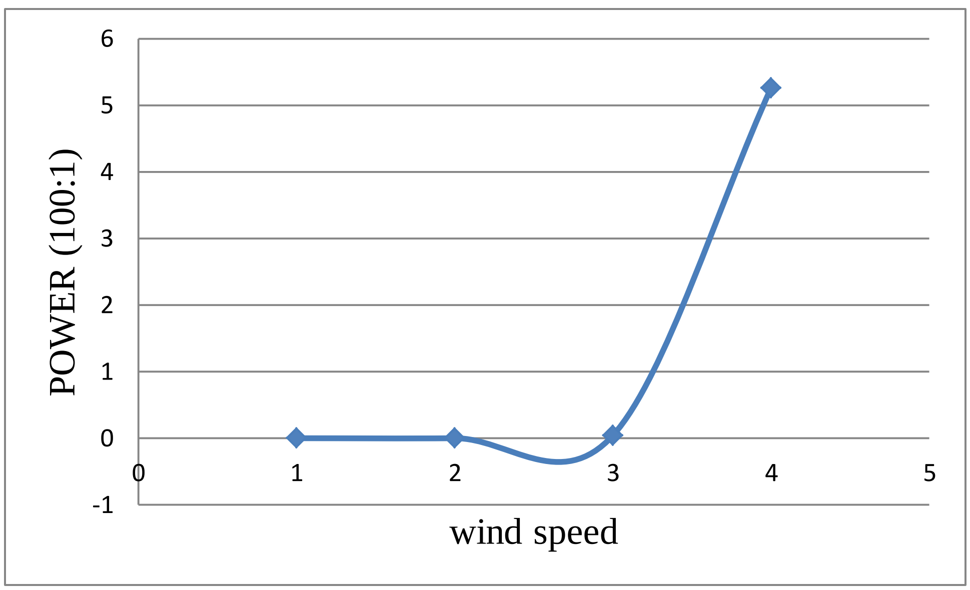


Figure 39 maximum power Vs wind speed

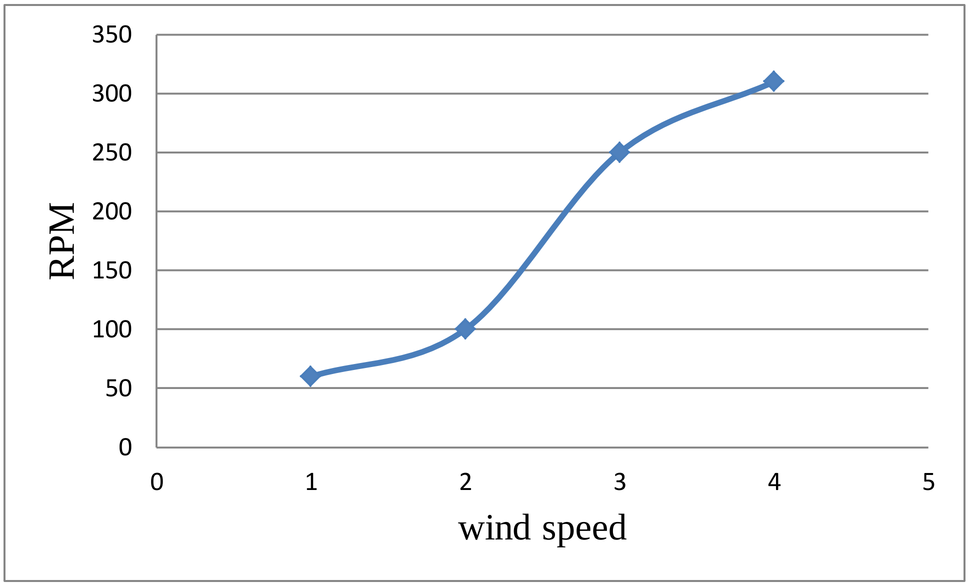


Figure 40: Maximum RPM vs wind speed

Computational Fluid Dynamics (CFD) Analysis

The purpose of this simulation is to obtain the wind speed difference between the concave and convex surface. The wind speed difference between the concave and convex blade surface of the Savonius rotor induced drag force that turns the blade. The speed difference was obtained by implementing Computational Fluid Dynamics (CFD) analysis on Solid Works Flow Simulation.

The engineering goals for the external analysis are two Surface Goals and four Global Goals. The two Surface Goals are dealing with total wind speed, for both concave and convex surface. The four Global Goals are deal with total pressure, velocity, normal force and force. This is listed on appendix 3.

The flow type of Savonius rotor blade is considered as external flow since it involves a solid model which is fully surrounded by the flow. The fluid flow is not bounded by outer surface, but bounded only by the Computational Domain boundaries. The Computational Domain is firstly defined to 7m x 7m x 9 m, which means that the Savonius rotor is enclosed by this region and the volume is fixed within this fluid flow field as shown in Figure 41. The Computational Domain can be set in different size, however, the bigger the Computational Domain, the longer the meshing and solution time.

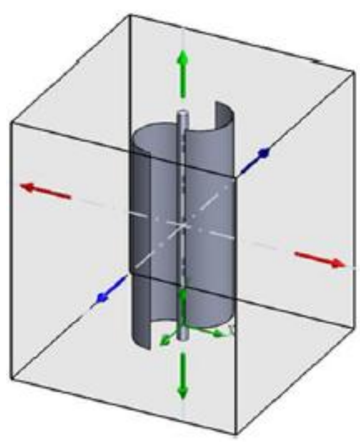


Figure 41 Computational domain for Savonius rotor in external flow analysis.

After the input data is ready, the model then is entering the meshing process. The meshing is viewed through a cut plot as shown in Figure 42. The fluid is experienced separation when it passes through the blade and this region is considered as high-gradient flow region. The mesh control is set to be finer in this region to obtain better solution accuracy.

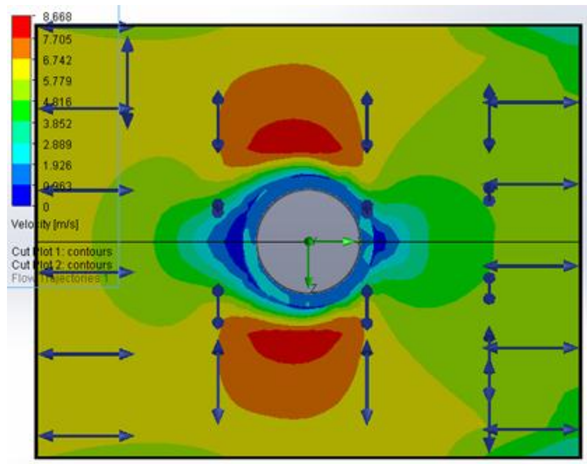


Figure 42: External flow velocity distribution

The wind speed distribution around the Savonius rotor is viewed by a contour cut plot from the top view. The contour cut plot display the higher wind speed region and lower wind speed region as red and blue color respectively. From Figure 42, the pressure is high near the concave surface and is low near the convex surface. The maximum and minimum wind speed is 8.668 m/s and 0 m/s respectively. The flow pattern is viewed by a flow trajectory is shown in Figure 43.

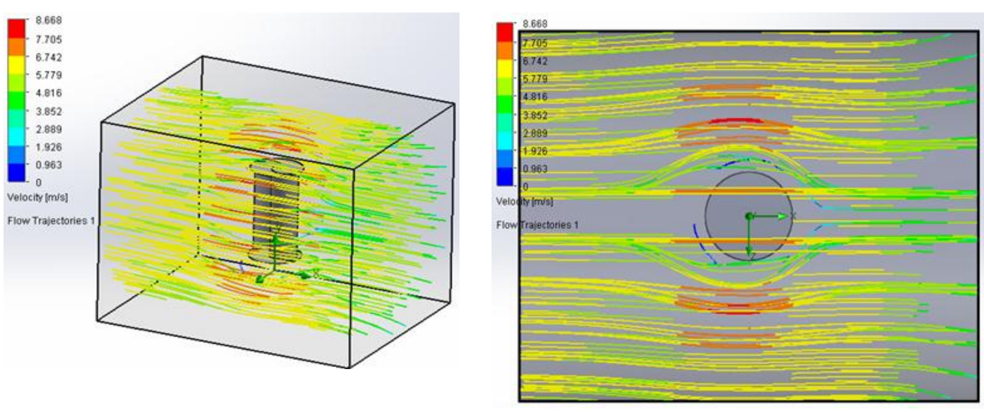


Figure 43: Flow pattern of external flow (Isometric view and top view)

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Our work and the results obtained so far are very encouraging and reinforce the conviction that vertical axis wind energy conversion systems are practical and potentially very contributive to the production of clean renewable electricity from the wind even under less than ideal sitting conditions. It is hoped that they may be constructed used high-strength, low- weight materials for deployment in more developed nations and settings or with very low tech local materials and local skills in less developed countries. The Savonius wind turbine designed is ideal to be located on top of a bridge or bridges to generate electricity, powered by wind. The elevated altitude gives it an advantage for more wind opportunity. With the idea on top of a bridge, it will power up street lights and or commercial use. In most cities, bridges are a faster route for everyday commute and in need of constant lighting makes this an efficient way to produce natural energy

5.2 Recommendation

The wind tunnel used on this research has a test section of 40 cm x 40 cm in cross section, which is very small for performance evaluation of a high solidity rotor. Therefore, it is better if a wind tunnel with a test section, large enough to accommodate the rotor and to reduce the blockage effect, is used for such an experiment.

The other difficulty of this project is the alternator because the appropriate wind speed alternator is not available in the market; we used car alternator b/c of this problem we couldn't get the expected result. So we recommend using a wind turbine alternator to see better performance. It is recommended to use wind turbine dynamometer with necessary instrumentation to measure the torque. Even though wind turbine dynamometer available in the lab there is appropriate instrumentation for measuring.

The time and budget should be improved for the future project work. Such type of the project should be encouraged by the government to be done since such project gives all rounded benefits to the society.

5.3 Future developments

We hope this study would lead to further research on the subject of counter rotating wind turbines. The development of effective alternators and dynamos can be used to harness wind energy from relatively small winds. The use of materials like Acrylic Plastic Sheets can be used to develop low cost Savonius VAWT. In addition, the necessity of gear sets to increase the relative shaft speed should be taken into account. May be planetary gear sets with a fixed ring gear with sun and at least three planet gears could be suggested to increase the speeds. Also if the planet gear could be correctly mounted, then the two middle bearing would be eliminated, which would decrease the cost.

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APENDIX-1 National meteorological agency Adama branch directorate

Average wind speed per each month for 5 years

Month	YEARS				
	2010	2011	2012	2013	2014
Jan	4.774194	5.006452	3.032258	4.76129	4.787097
Fe	2.890323	3.470968	4.587097	4.76129	3.896774
Mar	3.548387	3.787097	5.348387	3.793548	4.419355
Apr	3.064516	3.56129	5.316129	3.096774	4.064516
May	2.883871	3.883871	5.051613	4.219355	4.148387
Jun	4.032258	9.535484	3.375484	5.258065	4.729032
Jul	2.864516	3.477419	4.56129	4.909677	4.96129
Aug	3.63871	3.322581	8	4.529032	4.212903
Sep	5.445161	2.645806	4.890323	3.870968	2.993548
Oct	4.141935	4.870968	5.530968	3.529032	3.96129
Nov	2.851613	3.845161	5.019355	4.606452	4.987097
Dec	3.96129	5.070968	5.070968	4.651613	4.916129
AWSPY	3.674731	4.373172	4.981989	4.332258	4.339785

Station:-Nazret					'Element :- Monthly Average Max.Temp.(^{o}C)							
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2005	26.6	29.6	29.9	30.2	29.1	29.6	25.6	26.7	27.6	28.9	27.5	26.3
2006	27.5	28.7	28.6	28.8	30.6	29.9	25.9	25.2	26.4	27.9	26.9	25.1
2007	26.2	28.4	29.8	28.7	30.9	28.2	25.7	25.4	26.4	27	26.1	25.4
2008	26.8	27.1	30.4	29.7	30.1	28.5	25.4	25.2	26.9	27.3	24.7	25.1
2009	25.8	28	30.2	29.8	30.9	31.5	26.8	26.2	28.7	27.1	27.2	26
2010	26.6	27.3	27	29.9	30.2	29.8	25.8	26	26.7	28.2	27.2	26.1
2011	27.3	29.4	29.4	31.7	30.8	30	27.4	26.2	26.7	27.9	26.9	25.1
2012	25.5	27.4	29.7	29.4	30.4	29.8	24.8	24.5	26.5	27.3	27.5	26.7
2013	27.31	29.41	31.01	31.2	31.15	30.35	26.08	26.32	27.99	28.08	27.48	26.35
2014	28.1	29.5	29.8	30.7	31.4	31.6	28.3	26.7	27.3	26.9	27.5	26.2

Station :-Nazret   Element :-Monthly Average Min.Temp.(^{o}C)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2005	13.3	14.9	16.4	16.4	16.8	17.7	16.4	16.4	16.2	14.5	14.5	12.2
2006	14	15.8	15.4	15.6	16.8	17.8	16.6	16.1	16.1	15.2	14.8	14.7
2007	14	15.8	16.1	16.5	17.9	17.6	16.7	15.6	16.5	13.1	14.1	11.6
2008	13.9	13.7	14	16.8	17.3	16.8	15.5	15.4	15.9	14.6	12.8	12.1
2009	13.5	15.2	16.8	17.1	17.5	18.4	16.8	16.7	16.3	14.3	13.3	15
2010	14.1	15.4	15.3	16.2	17.4	17.8	16.5	16.9	15.2	14.5	13.9	11.6
2011	13.1	14.2	14.9	16.6	16.3	16.8	16.6	16.7	15.6	14.2	14.9	12.7
2012	14.1	14.2	16.4	16.9	17	23.8	15.9	16	15.9	13.7	13.9	14.4
2013	14.3	15.1	17.3	17.4	18.3	18.2	15.6	16.7	15.9	14.8	14.2	11.9
2014	13.9	16.4	16.7	17.4	17.3	18.1	17.1	16.5	16	14.7	15	13.3

Note: - ---------------> NA ----------------> Data not Available

Adama Station-

Longitude=8°33”23.8’N   .
Latitude=39°17”02.5”E
Dominating climate of the city is hot/arid climate type

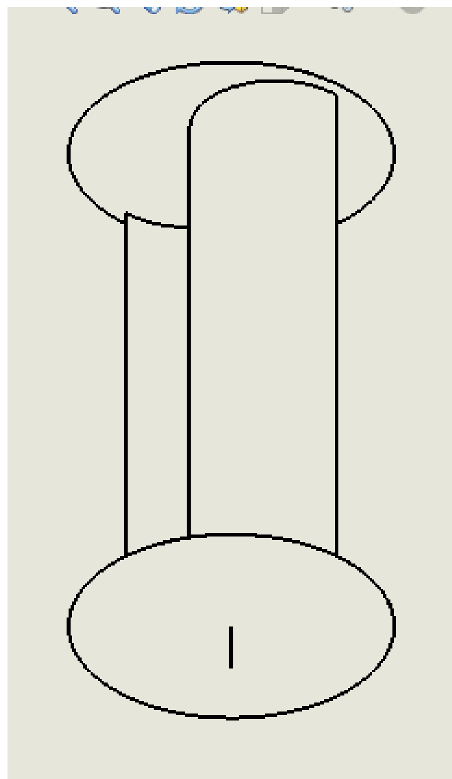
Altitude = 1648m above sea level

Distance from Addis Abeba is 99 km

Meteorological seasons

- Bega: October –January
- Belg: February – May
- Kiremt: June –September

Appendix 2 prototype of the Savonius rotor wind turbine and wind tunnel test



The prototype of the Savonius rotor wind turbine

Wind tunnel testing

Appendix 3 Calculation Mesh & Basic Mesh Dimensions

Number of cells in X	36
Number of cells in Y	28
Number of cells in Z	28

Number of Cells

Total cells	102165
Fluid cells	67788
Solid cells	4428
Partial cells	29949
Irregular cells	0
Trimmed cells	0

Maximum refinement level:

Goals

Name	Unit	Value	Progress	Use in convergence	Delta	Criteria
GG Min Total Pressure 1	Pa	100354.10	37	On	2170.96284	804.006923
GG Max Total Pressure 1	Pa	101933.81	100	On	1322.35111	2014.46124
GG Force 1	N	2.799	100	On	34.1959623	71.6868324
SG Force 1	N	2.799	100	On	34.1959623	71.6868324
SG Torque (Y) 1	N*m	-0.147	100	On	0.617453532	2.59376338

Min/Max Table

Name	Minimum	Maximum
Pressure [Pa]	100353.75	101931.14
Temperature [K]	290.97	293.21
Density (Fluid) [kg/m^3]	1.20	1.21
Velocity [m/s]	0	8.668
Velocity (X) [m/s]	-8.660	4.464
Velocity (Y) [m/s]	-3.339	4.759
Velocity (Z) [m/s]	-4.689	4.664
Temperature (Fluid) [K]	290.97	293.21
X (cartesian) [m]	-1.590	1.590
Y (cartesian) [m]	-0.524	1.996
Z (cartesian) [m]	-1.260	1.260
Phi (cylindrical) [rad]	0	6.283
Radius r (cylindrical) [m]	0.002	2.534
Z-axis (cylindrical) [m]	-1.260	1.260
Phi (spherical) [rad]	0	6.283
Theta (spherical) [rad]	-1.527	1.527
Position Vector R (spherical) [m]	0.003	2.534
Mach Number [ ]	0	0.03
Vorticity [1/s]	0.001	2508.421
Velocity RRF [m/s]	0	49.479
Velocity RRF (X) [m/s]	-47.281	47.269

Velocity RRF (Y) [m/s]	-3.339	4.759
Velocity RRF (Z) [m/s]	-47.196	47.172
Mach Number RRF [ ]	0	0.14
Shear Stress [Pa]	0	0.92
Relative Pressure [Pa]	-971.25	606.14
Heat Transfer Coefficient [W/m^2/K]	0	0
Surface Heat Flux [W/m^2]	0	0
Turbulence Length [m]	1.299e-006	0.055

APPENDIX: 4: Dimensions of normal-profile belts

Classical belt	ISO marking	Z	A	B	-	C	-	D	E
	DIN marking	**10**	**13**	**17**	**20**	**22**	**25**	**32**	**40**
approximate upper width l_0		10	13	17	20	22	25	32	40
pitch width l_p		8,5	11	14	17	19	21	27	32
belt height h_0		6	8	11	12,5	14	16	20	23
height under pitch line b_p		2,5	3,3	4,2	4,8	5,7	6,3	8,1	9,6
minimal pulley pitch diameter $d_{p\ min.}$		50	71	112	160	180	250	355	500
1 m belt mass [kg] ≈		0,07	0,12	0,20	0,27	0,37	0,44	0,69	1,03

APPENDIX: 5: Recommended length of normal-profile length of v-belt hand book

Code	Internal length L_i (mm)	Code	Internal length L_i (mm)	Code	Internal length L_i (mm)	Code	Internal length L_i (mm)	Code	Internal length L_i (mm)	Code	Internal length L_i (mm)	Code	Internal length L_i (mm)	Code	Internal length L_i (mm)	Code	Internal length L_i (mm)
A 15	382	A 28	710	A 36 1/2	925	A 43 3/4	1111	A 53 1/4	1355	A 70	1775	A 86	2187	A 107	2725	A 147	3737
A 18	457	A 28 1/2	724	A 37	942	A 44	1120	A 54	1372	A 71	1800	A 87	2212	A 108	2743	A 148	3750
A 19	480	A 29	737	A 37 1/4	946	A 44 1/2	1132	A 55	1400	A 72	1825	A 88	2240	A 110	2800	A 155	3937
A 20	508	A 29 1/2	750	A 37 1/2	950	A 45	1143	A 56	1422	A 73	1854	A 89	2267	A 112	2845	A 158	4000
A 21	535	A 30	767	A 38	965	A 45 1/2	1150	A 57	1450	A 74	1880	A 90	2286	A 113	2870	A 162	4115
A 22	560	A 30 1/2	775	A 38 1/2	975	A 46	1168	A 58	1475	A 75	1900	A 91	2311	A 114	2896	A 167	4250
A 23	587	A 31	787	A 39	992	A 46 1/2	1180	A 59	1500	A 76	1930	A 92	2337	A 116	2946	A 173	4394
A 23 1/2	600	A 31 1/2	800	A 39 1/2	1000	A 47	1200	A 60	1525	A 77	1956	A 93	2360	A 118	3000	A 180	4572
A 24	610	A 32	813	A 40	1016	A 48	1220	A 61	1550	A 78	1980	A 94	2388	A 120	3048	A 187	4750
A 24 1/2	620	A 32 1/2	825	A 40 1/2	1030	A 48 1/4	1225	A 62	1575	A 79	2000	A 95	2413	A 124	3150	A 197	5000
A 24 3/4	630	A 33	838	A 41	1041	A 49	1250	A 63	1600	A 80	2032	A 96	2438	A 128	3250	A 217	5477
A 25	637	A 33 1/4	847	A 41 1/2	1050	A 50	1270	A 64	1625	A 81	2060	A 97	2464	A 130	3302		
A 25 1/2	647	A 33 1/2	850	A 41 3/4	1060	A 51	1300	A 65	1650	A 82	2083	A 98	2500	A 132	3350		
A 26	660	A 34	867	A 42	1067	A 51 1/2	1307	A 66	1676	A 83	2100	A 100	2540	A 134	3404		
A 26 1/2	670	A 34 1/2	875	A 42 1/2	1075	A 52	1320	A 67	1700	A 83 1/2	2120	A 102	2591	A 136	3454		
A 27	686	A 35	900	A 43	1100	A 52 1/2	1337	A 68	1725	A 84	2134	A 104	2650	A 140	3550		
A 27 1/2	700	A 36	914	A 43 1/2	1105	A 53	1346	A 69	1750	A 85	2160	A 105	2667	A 144	3658		