



**Addis Ababa University**  
**Addis Ababa Institute of Technology**  
**School of Graduate Studies**  
**School of Mechanical and Industrial Engineering**

**Feasibility Study of Use of a Horizontal Axis  
Aerogenerator for Well Water Lifting in Borena**

**A thesis submitted to the School of Graduate Studies of Addis Ababa institute of  
Technology in partial fulfillment of the Masters of Science in Mechanical Engineering  
(Thermal Engineering Stream)**

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**2013**

**Addis Ababa University**  
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## Declaration

### Addis Ababa University School of Graduate Studies

This is to certify that the thesis prepared by Mesay Mekonnen, entitled: *Feasibility Study of Use a Horizontal Axis Aerogenerator for Well Water Lifting in Borena* and submitted in partial fulfilment of the requirements for the degree of Degree of Master of Science (Thermal Engineering) complies with the regulation of the university and meet the accepted standards with respect to originality and quality.

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## Nomenclature

$P_h$	hydraulic pump power, [W]	$P_W$	average wind machine power, [W]
$\rho_w$	density of water, [kg/m <sup>3</sup> ]	$E_W$	average wind machine energy, [kWh]
$g$	gravitational acceleration, [m/s <sup>2</sup> ]	$c$	Weibull scale parameter, [m/s]
$Q$	flow rate of water, [m <sup>3</sup> /s]	$k$	Weibull shape parameter $f(V)$
$H$	total pumping head, [m]		probability density function
$\alpha$	ground surface friction coefficient	$F(V)$	cumulative distribution function
$V_h$	wind speed at height $h$ , [m/s]	$P_{av}$	average wind machine power, W
$V_r$	wind speed at height $r$ , [m/s]	NPV	net present value, [ETB]
$h$	height above the ground surface, [m]	$B_A$	annual benefit, [ETB]
$\rho_a$	air density, [kg/m <sup>3</sup> ]	$C_i$	capital investment, [ETB]
$V$	wind speed, [m/s]	$n$	life time of the system
$P$	wind power, [W]	$r$	real rate of interest
$C_p$	turbine power coefficient	$m$	maintenance cost factor
$A$	swept area of turbine blades, [m <sup>2</sup> ]	$E_A$	annual energy production, [kWh]
$E$	kinetic energy, [J]	$P_e$	electricity price, [ETB/KWh]
$m$	mass of air, [kg]	$i$	annual inflation rate
$D$	diameter of turbine, [m]	PP	payback period [year]
$t$	time, [s]	IRR	internal rate of return
$V_{av}$	average wind speed, [m/s]	$h_r$	reference height at which wind speed is measured, [m]
$z$	elevation above sea level, [m]	$\frac{P_{av}}{A}$	average wind power density per unit area, [W/m <sup>2</sup> ]
WPD	wind power density, [W]	$\frac{E_{av}}{A}$	average wind energy density per unit area, [kWh/m <sup>2</sup> ]
$N$	number of wind speed readings	$\Delta t$	desired time interval to calculate average energy, [s]
$Q_T$	total water consumption per day	$P(V_1 < V < V_2)$	probability of wind speed being between $V_1$ and $V_2$
$E_h$	hydraulic pumping energy, [J]	$P(V > V_x)$	probability of wind speed exceeding $V_x$
$\bar{V}$	volume of water, [m <sup>3</sup> ]		
$\eta$	overall efficiency		
$\eta_p$	pump efficiency		
$P_p$	required pump power, [W]		
$V_m$	mean wind speed, [m/s]		
$V_i$	wind speed at the $i^{th}$ reading, [m/s]		

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## List of Abbreviations and Acronyms

asl	above sea level
NMSA	National Metrology Service Agency
WECS	Wind Energy Conversion System
Eq.	Equation
WPD	Wind Power Density
WED	Wind Energy Density
HAWTs	Horizontal Axis Wind Turbines
VAWTs	Vertical Axis Wind Turbines
ETB	Ethiopian Birr
EEPCO	Ethiopian Electric Power Corporation
CSA	Central Statistical Authority
WTG	Wind Turbine Generator

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## Abstract

Feasibility Study of Use of a Horizontal Axis Aerogenerator for Well Water Lifting in Borena

Mesay Mekonnen

Addis Ababa University, 2013

Shortage of water or problem of accessing it will cause a decrease in the income from agro-pastoral activities like the production of livestock, livestock products and small scale agriculture. To make sure that there is a continuous income generating from livestock production and small scale agricultural activities, the availability and amount of water supply is essential. Although the Ethiopian Electricity Power Corporation supplies electrical energy to consumers at low prices, extending the service to the remote area of the country may be costly. Due to its damaging effects on the environment and highly increased cost, use of diesel energy as the source power in remote areas is not recommended. Therefore, considering the global warming the most serious problem facing the global community, use of renewable energy is the best alternative energy solution. Therefore, in this research, a detail investigation has been made to determine the feasibility of using wind power for extracting well water in the Borena site for limited number of households. Six years wind data of Borena site and seven different sizes of horizontal axis small aero-generators have been considered for the study. Statistical analysis of the raw wind speed data has been carried out by using MATLAB R7.12 program. The results of the research shows, the Borena site has an average wind speed 4.8m/s and wind power density 73.8W/m<sup>2</sup> at 25m, which is applicable for small wind turbines. Then, economic analysis is done to identify the most profitable wind turbine. Finally, the *SkyStream 3.7* is feasible regarding its performance and profitability for extracting well water in the Borena site.

## **Chapter 1: Introduction**

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In most arid areas of Ethiopia, the majority of the community members are pastoralists or agro-pastoralists, and livestock holdings mostly determine the level of household wealth. The main livestock kept in the areas include cattle, sheep, goats, and camels, which requires a large amount of water in parallel with their diet.

Borena is one of the areas found in the southern Ethiopia (Oromia) and northern Kenya having semi-arid climate with average annual mean temperatures vary from 19 to 24°C and annual rainfall ranging between 350mm and 900mm. The Borena plateau or zone occupies a total area of about 95,000 square kilometers and its altitude ranges from 1,600 meters above sea level in the northeast to about 1,000 meters above sea level in the extreme south of Ethiopia. The region is dominated by savannah containing mixtures of perennial herbaceous and woody vegetation. Several native species of grasses and woody plants provide excellent forage during the rainy season but deteriorate in the dry season and, therefore, the major limiting resource is underground and surface water. There are deep wells (Tula wells) and dispersed springs used to supply water for the society and their cattle's. The deep wells are perhaps the most fundamental feature that has shaped the Borena society, constituting a vital source without which keeping cattle in the Borena ranges would be impossible in the dry season. Tula wells are old, usually much deeper than normal wells comprise the most reliable source of water, never drying up even in the course of severe draughts [21].

### **1.1. Statement of the Problem**

Shortage of water or problem of accessing it will cause a great role in disturbing the development of agro-pastoral activities like the production of livestock, livestock products and small scale agricultural activities. This would indirectly affect the country's economy. Therefore, the main feature of this research is to solve problems of accessing water by using appropriate horizontal axis aerogenerator and pump system for the Borena region of limited number of households.

One may ask why the research is necessary, but there are some important points that the project could answer. Firstly, there are several ways of accessing water from the well or underground. Accessing well or underground water by itself requires an energy that is going to run the pump. While applying energy for lifting from such water sources, there should be careful selection of

type of energy resource. For example, global warming is considered one of the most serious problems facing the global community. Certain gases, such as carbon dioxide, when released in the atmosphere through the burning of fossil fuels, create a “greenhouse effect.” Clean, renewable energy solutions, such as wind, solar and hydroelectric systems, that do not rely on fossil fuel for energy production curb the effect of global warming. This paper aims to focus on the renewable energy specifically the wind energy through horizontal axis wind turbine, which will remain a useful power source. Therefore, it is preferred to consider some points listed below while selecting appropriate type of energy,

- Availability of energy source,
- Potential of the available energy, and
- Environmentally clean energy type, etc...

Upon considering those mentioned criteria, wind energy is clean, quiet and efficient for small wind turbines in this semi-arid region.

Secondly, the source of income in many parts of Borena is sales of animals mainly cattle and camels. Obviously, the Borena cattle are good source of beef for local and international markets. For example, over 90% of the livestock exported for slaughter from Ethiopia come from lowland areas, where Borena cattle form the majority [22]. Here, the communities are not restricted only to livestock production, but also they have experienced individual crop cultivation. This process of agricultural activities will directly enhance the preparation of their cattle’s diet (rangeland) and make them to be self-dependent on their food security. Therefore, to make sure that there is a continuous income generating from livestock production and to be self-dependent on their food security, the availability and amount of water supply plays a significant role. As the same time the water is exposed to the surrounding atmosphere. But by using the pumping system it is possible to enclose the well, as a result, reducing livestock disease due to contamination of water.

The third issue but not the least is that it creates the situation for the young men to be more productive and have additional income by providing them with small scale agricultural activities rather than wasting their time by lifting up water from the deep well.

As illustrated in the Figure 1.1 the Borena young people gather the water from the lowest level, pass the containers up to one person above them and put it in the next higher trough up the wall

of the well. This may be repeated several times, the water being passed up by hand from trough to trough up the sides of the well until it reaches the trough where the cattle are drinking.



Figure 1.1: Two men delivering well water.

## **1.2. Objectives**

This research is carried out to investigate the wind energy potential of Borena site using various commercially available Horizontal Axis Wind Turbines (HAWTs) for water pumping purpose. After having a series of processes, the system that seems feasible for the site (with regards to better energy generation and economically less expensive) would be selected.

The specific objectives of this thesis are, therefore:

- Estimating the daily water consumption of limited number of households;
- Collect wind speed data from the National Metrology Service Agency;
- System modeling for wind energy source at the selected site using analytical methods;
- Data analysis and resource estimation, and
- Estimate the economics of the system and compare their feasibilities among different wind turbine types.

### **1.3. Methodology**

The first step when modeling water pumping system needs to know the volume of water consumption per day and the depth of the well from which the water is being lifted, thus having the two main criteria the amount of energy needed to pump water to the required depth could be known.

The volume of water required per day is determined based on the number of population considered and the type of application of water they are used. The total head  $H$  comprises the sum of the static head and the head loss in pipes, which depends on the pipe diameter and flow rate. Thus, the power required to lift a given volume of water into a total head is expressed as:

$$P_h = \rho_w g Q H \quad \text{--- (1.1)}$$

After the flow rate and total dynamic head have been determined. One can select a pumped based on the manufacturer's catalogue information using the total head and flow required as well as suitability to the application.

Wind speed data from NMSA (National Metrology Service Agency) for the years 2004-2009 were used to generate statistics to examine the wind power potential of Borena. The data contains daily wind speed of the site measured at 2m above the ground.

Generation of rated power from a wind turbine requires continuous flow of wind at a rated speed. This is difficult to accomplish because wind by its very nature is not constant and does not prevail at a steady rate. It fluctuates during short period of time. The speed of wind is also dependent on height above the ground. In order to estimate the wind speed at any height, Hellmann's exponent law can be used:

$$\frac{V_h}{V_r} = \left( \frac{h}{h_r} \right)^\alpha \quad \text{--- (1.2)}$$

Where  $V_h$  is the wind speed at height  $h$  and  $V_r$  is the wind speed at height  $h_r$  and  $\alpha$  is the Hellmann's exponent. For flat and open area  $\alpha$  is approximately equal to one seventh. The available power in wind at any wind speed may be estimated as:

$$P = \frac{1}{2} \rho_a V^3 \quad \text{--- (1.3)}$$

where  $\rho_a$  is the air density, which was assumed to be  $1.049 \text{ kg/m}^3$  and  $V$  is monthly mean wind speed in m/s. This available power cannot be totally extracted by any wind machine. The

maximum extractable power from any wind machine is limited by famous Betz relation [Betz 1942] which assigns power co-efficient  $C = 16/27$  for the maximum performance of a wind machine.

$$P_{WECS} = C_p \left[ \frac{1}{2} \rho_a A V^3 \right] \quad \text{--- (1.4)}$$

Then, the input energy undergoes several conversions before it is made available as useful hydraulic energy. Finally, the available power of the system is expressed as:

$$P_h = \eta C_p \left[ \frac{1}{2} \rho_a A V^3 \right] \quad \text{--- (1.5)}$$

Based on the wind data analysis several types of WECS may satisfy the energy requirement. However, to select the system which seems feasible will be determined by carrying out economic comparison for each wind turbines.

#### **1.4. Outline of the Report**

Chapter two reviews literature about basic theory of wind energy assessment, basics of wind turbine, wind electric water pumping system and previous works on wind pumping systems and wind energy in Ethiopia. Chapter three estimates the daily water demands of the Borena's community and sizing of system components. Chapter four describes the analysis of wind data and estimation of the resource using statistical methods. Chapter five is about techniques of wind turbine generator selection and system design. The results and discussion of the final output is discussed in chapter six. Chapter seven summarizes the whole work and set up some recommendations.

## Chapter 2: Literature Review

---

It is commonly accepted that the earth's fossil energy resources are limited, and the global oil, gas and coal production will come beyond their peak in the decades, and price rises will continue. Renewable energies are climate-friendly forms of energy, due to absence of emissions detrimental to the environment. The savings especially in carbon dioxide and sulphur dioxide emissions are a significant advantage over fossil power stations.

Wind energy is one of the leading renewable energy resources that are not exhausted over time. It is a good resource for the reason that it cannot only produces little or no polluting emissions, but also can help to meet the growing energy demand. It has been harnessed for thousands of years. The wind energy can be converted into other forms of energy, either electrical or mechanical energy. One of the oldest uses of wind energy is transportation, people use it to sail ships, and farmers also have been using wind energy to pump water, grind grain. More recently, it has been widely used for special purposes in the world, such as generating electricity, and modern wind turbines are the machines which are extremely efficient converting the wind energy into electricity. The main goal of this research is to determine whether pumping well water using aerogenerator (wind turbine generator) for Borena site is feasible or not.

### 2.1. Basic Theory of Wind Energy Assessment

The terms "wind energy" or "wind power" describe the process by which the wind is used to generate mechanical power or electricity. Wind turbines convert the kinetic energy of the wind into mechanical power. This mechanical power can be used for specific tasks (such as grinding grain or pumping water) or a generator can convert this mechanical power into electricity to power homes, businesses, schools, and the like.

Any moving object has kinetic energy. In classical mechanics, its amount  $E$  in joules is given by the Eq. (2.1), where  $m$  is the mass in kg, and  $V$  is the air speeds in m/s. Air molecules have mass, and when they are in motion, they contain kinetic energy that can be converted into other forms for practical use [24].

$$E = \frac{1}{2} m V^2 \quad \text{--- (2.1)}$$

When an air molecules hit a surface of any object that is allowed to move, their motion is partially transferred to the moving object. Particularly, in wind turbines the energy is extracted

from the air as it moves through the "swept area" of the turbine's blades: the air turns the aerodynamically designed blades, which transfer this harvested energy into a spinning shaft. The shaft is connected to a generator's rotor whose motion makes electricity.

### 2.1.1. Available wind power

The diagram below illustrates wind energy transfer. If  $D$  is the diameter of the turbine's blade, they intercept the air in the cross-sectional area  $A = \frac{\pi}{4} D^2$ .

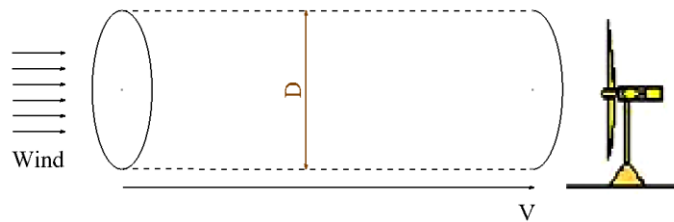


Figure 2.1: Flow of air through a rotor disk.

In a time  $t$ , the mass of the air molecules that will pass through this area is  $m = \rho_a V t$ , where  $\rho_a$  is the density of the air (approximately  $1.225 \text{ kg/m}^3$  at sea level) [19]. By combining the above formulas, we find the energy of the air that passes through the area  $A$  in a time  $t$ :

$$E = \frac{1}{2} \rho_a A V^3 t \quad \text{--- (2.2)}$$

Then power in watts being  $E$  per unit time is given by [24]:

$$P = \frac{1}{2} \rho_a A V^3 \quad \text{--- (2.3)}$$

Note that to get the result in watts, all the values in these formulas have to be expressed in SI units. We see that power available in the wind is proportional to the cube of its speed and the size of the turbine's blades. If for example, the speed doubles, then the available watts increase by a factor of eight.

### 2.1.2. Wind speed variation with height

The turbine hub must be erected at a height that is clear of any obstructions like trees and buildings. These obstructions cause turbulence which not only reduces the air stream through the blades and reduces the power that can be developed, but also places fatigue loads on the

blades. A good rule of thumb is to always place the hub away from the highest obstruction at a distance of more than twice the height of this highest obstruction.

Wind speed increases with an increase in height because the air offers less resistance to airflow than the surface of the earth. The turbine would therefore experience increased wind speeds when it is erected high and can potentially extract more power from the air. But as the height of the tower increases the initial capital cost, maintenance and operation costs increases, so it is a compromise issue.

In wind energy studies, two mathematical models or ‘laws’ have generally been used to model the vertical profile of wind speed. The first approach, the log law, has its origins in boundary layer flow in fluid mechanics and in atmospheric research. It is based on a combination of theoretical and empirical research. The second approach, used by many wind energy researchers, is the power law. Both approaches are subject to uncertainty caused by the variable, complex nature of turbulent flows [19].

The wind shear at ground surface causes the wind speed increase with height in accordance with the power law expression:

$$V_2 = V_1 \left( \frac{h_2}{h_1} \right)^\alpha \quad \text{--- (2.4)}$$

where  $V_1$  is the wind speed measured at the reference height  $h_1$ ,  $V_2$  is the wind speed estimated at height  $h_2$ , and  $\alpha$  is ground surface friction coefficient.

Table 2.1: Friction Coefficient of Various Terrains.

---

<b>Terrain Type</b>	<b>Friction Coefficient <math>\alpha</math></b>
Lake, ocean and smooth hard ground	0.10
Foot high grass on level ground	0.15
Tall crops, hedges, and shrubs	0.20
Wooded country with many trees	0.25
Small town with some trees and shrubs	0.30
City area with tall buildings	0.40

---

Gaining even a small increase in velocity boosts a turbine’s generating potential significantly since the cube of wind speed and power are directly related. The friction coefficient is low for smooth terrain and high for rough ones (Figure 2.2). The values of  $\alpha$  for typical terrain classes are given in Table 2.1 above [24].

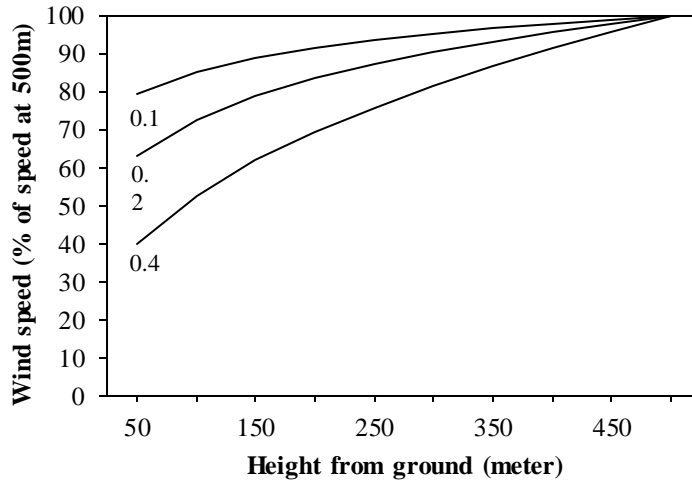


Figure 2.2: Wind speed variation with height over different terrain [24].

In the Borena site the geographical situation is somewhat covered with relatively medium crops, hedges, and shrubs. Assume that the wind pumping system is to be installed near the end user’s village. Then considering the effects of the houses and geographical situations on the wind, I have approximated the value of friction coefficient,  $\alpha$  to be 0.25. Substitute the given values i.e.,  $h_1 = 2\text{m}$ ,  $V_1 = V_{av} = 2.55\text{m/s}$ ,  $\alpha = 0.25$  into Eq. (2.4) and calculate for  $V_2$ , then one can determine the velocity of the air at the corresponding height from the ground. Figure 2.3 shows clearly the variation of wind speed with respect to height of the hub.

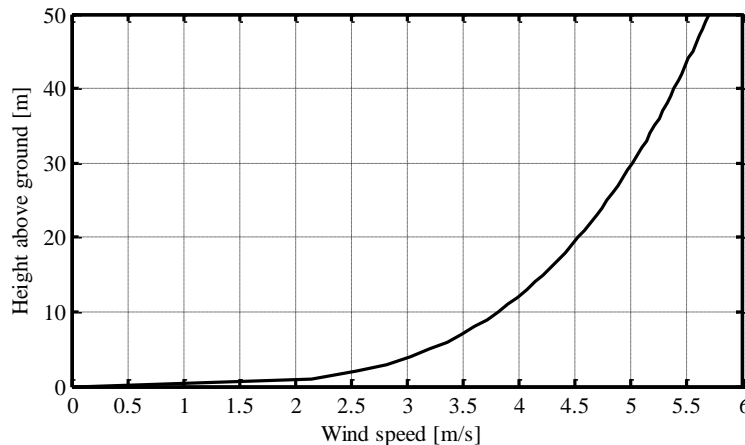


Figure 2.3: Wind Speed Shear Profile.

### 2.1.3. Wind power density and air density

Wind power density is defined as the wind power available per unit area swept by the turbine blades. It is an actual indicator of wind energy potential of a given site. Wind power density is a function of the air density. Therefore, air density must be taken into account when installing turbines at sites with high elevations above sea level. This is because air density decreases at high altitudes and could reduce the power that can be extracted from the air by the turbine according to Eq. (2.3). The air density,  $\rho_a$ , at a specific height above sea level can be calculated by the expression:

$$\rho_a = 1.225 - (1.194 \times 10^{-4})z \quad \text{--- (2.5)}$$

where,  $z$  = the location's elevation above sea level in m [24].

Wind power density is calculated using the following equation:

$$\text{WPD} = \frac{1}{2} \rho_a V^3 \quad \text{--- (2.6)}$$

Note that the expression in Eq. (2.7) for WPD is a simplification that holds the assumption that the wind blew with speed  $V$  all the time. In reality, varying winds mean we must work a little harder to find the true WPD. To get the most accurate estimate for the Wind Power Density, one must actually perform a summation using data taken over time, as follows.

$$\text{WPD} = \frac{1}{2} \frac{1}{n} \sum_{i=1}^n (\rho_i V_i^3) \quad \text{--- (2.7)}$$

where  $n$  is the number of wind speed readings,  $\rho_a$  is the air density ( $\text{kg/m}^3$ ),  $V_i^3$  is the cube of the  $i^{\text{th}}$  wind speed (m/s) value [24].

### 2.1.4. Wind power class

It is defined as the way of quantifying on a scale the strength of the wind at a project site. The Department of Energy's National Renewable Energy Laboratory defines the wind class at a site on a scale from 1 to 7 (1 being low and 7 being high) based on average wind speed and power density to offer guidance to potential developers as to where wind projects might be feasible. Table 2.2 shown below provides average wind power density in watts per one square meter of a turbine sweep area. Average speeds in the table are based on the so-called Rayleigh speed distribution and are given for the sea level. To get the same density above sea level, the air speed has to increase by 3% per 1000 meter (1% per 1000ft) elevation [19].

Table 2.2: Classes of wind power density at 10m and 50m [19].

<b>Wind Power Classes</b>	<b>10 m (33 ft)</b>		<b>50 m (164 ft)</b>	
	<b>Wind Power Density [W/m<sup>2</sup>]</b>	<b>Average Air Speed [m/s (mph)]</b>	<b>Wind Power Density [W/m<sup>2</sup>]</b>	<b>Average Air Speed [m/s (mph)]</b>
1	0-100	0-4.4 (0-9.8)	0-200	0-5.6 (0-12.5)
2	100-150	4.4-5.1 (9.8-11.5)	200-300	5.6-6.4 (12.5-14.3)
3	150-200	5.1-5.6 (11.5-12.5)	300-400	6.4-7.0 (14.3-15.7)
4	200-250	5.6-6.0 (12.5-13.4)	400-500	7.0-7.5 (15.7-16.8)
5	250-300	6.0-6.4 (13.4-14.3)	500-600	7.5-8.0 (6.8-17.9)
6	300-400	6.4-7.0 (14.3-15.7)	600-800	8.0-8.8 (17.9-19.7)
7	400-1,000	7.0-9.4 (15.7-21.1)	800-2,000	8.8-11.9 (19.7-26.6)

The table provides data only for 10 m and 50 m heights. To estimate the air speed and output for the actual height of your tower you can use an empirical 1/7 power law. If you know the air speed  $V_1$  at a certain height  $h_1$ , then the air speed  $V_2$  at a different height  $h_2$  can be estimated as:

$$V_2 = V_1 \left( \frac{h_2}{h_1} \right)^{1/7} \quad \text{--- (2.8)}$$

Note that the values in the above table were obtained for the sites that are free of obstructions. If you have any obstruction such as a tree or a building within 300 feet (100 meters), it is generally recommended to place the turbine at least 10 feet (3 meters) plus the blade length above the top of the highest obstruction [13].

## 2.2. Basics of Wind Turbines

A wind turbine is a machine that converts the kinetic energy from the wind into mechanical energy. If the mechanical energy is used directly by machinery, such as a pump or grinding stones, the machine is usually called a windmill. If the mechanical energy is then converted to electricity, the machine is called a wind generator [26].

Using wind turbines without connection to the grid (off-grid), it is widely used for a small application, housing light and charging a battery, pumping water, etc. With a small wind

turbine and a certain wind speed, it could supply the convenient electricity power (a few kW to around 10kW) [26]. It is also good for rural electrification, telecom, and other off-grid applications. The most obvious advantages of wind turbine of off-grid are easy to construct maintenance and remove.

Wind projects vary in size, from small projects of one to a few turbines serving individual customers to large projects designed to provide wholesale electricity to utilities or an electricity market. This research focuses on water pumping using small wind project for limited number of agro-pastorals living at Borena site. The site has annual average wind speed of 3.81 m/s at 10 meters and also belongs to a wind power class 1. This information leads to the use of small wind turbines for the project.

### **2.2.1. Wind turbine classification**

Modern wind turbines come in to two basic configurations based on the direction of the rotating shaft (axis):

- I. Horizontal axis wind turbine (HAWT) and
- II. Vertical axis wind turbine (VAWT)

They range in size from very small machines that produce a few tens or hundreds of watts to very large turbines producing as much as 5 megawatts of power. The three bladed rotors is the most important and most visible part of the wind turbine. It is through the rotor that the energy of the wind is transferred into mechanical energy that turns the main shaft of the wind turbine [9].

#### ***I. Horizontal axis wind turbine***

Most wind machines being used today are the horizontal axis type. Horizontal axis wind machines have blades like airplane propellers. Horizontal axis wind turbines (HAWTs) predominantly have 2 or 3 blades, or larger number of blades as can be seen in Figure 2.4. The latter are described as high solidity devices and include the multi blade wind turbines used for water pumping on farms. In contrast, the swept area of wind turbines with 2 or 3 blades is largely void; only small fraction of this area appears to be solid. These are referred to as low solidity devices.

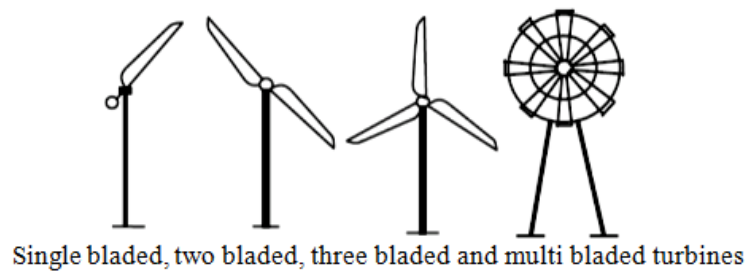


Figure 2.4: Horizontal axis wind turbine designs.

## II. Vertical axis wind turbine

Vertical axis wind turbines (VAWTs) have blades that go from top to bottom. The most common types of these turbines are Savonius and one of the most popular in the world market, Darrieus as shown in Figure 2.5. These turbines can harness winds from any direction without the need to reposition the rotor when the wind direction changes.

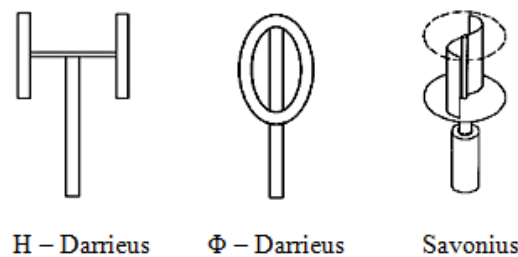


Figure 2.5: Vertical axis wind turbine designs.

The three bladed HAWT is the optimal low solidity design. It is superior to the single and two bladed designs because the three blades make it dynamically balanced and reduce wind noise. The design has a self-starting capability and higher power coefficient than the Darrieus design which makes it the preferred turbine choice for power generation at sites with medium to high wind regimes [10].

### 2.2.2. Small off-grid turbines

Small turbines are usually not connected to the grid and operate independently as battery chargers and pumping of water. This implies that the generator (and therefore the rotor) are not governed by the frequency of the grid and are completely free to follow the momentary conditions at variable rpm. Such turbines require critical control mechanisms for limiting the maximum rpm of the rotor and for preventing generator overload.

On the other hand, small turbines should be cheap and simple, while their masses and loads are comparatively small, so the employed control mechanisms are a benchmark for simplicity and robustness.

### ***Typical features of small off-grid turbines***

- Simplicity and maintenance-free operation are more important than higher energy efficiency for small turbines. This results in simplified blade profiles passive yawing, etc.
- Output regulation relies on systems for driving the rotor out of wind by yawing or furling (decreasing the rotor area exposed to wind).
- Induction generators are not good for off-grid applications. The most usual generator is the synchronous PM machine.
- Energy storage is required Electrical batteries with electronic charge controllers are usually used.
- The blades are simple and far from the optimum aerodynamic shape, usually make of wood or plastic.
- Yawing is passive, with the help of a tail vane and
- Small wind turbines can also have well-designed blades and nacelles.

### **2.2.3. Amount of electricity a turbine can generate**

Eq. 2.3 for P represents the amount of power in the imaginary tube of the air that flows through the turbine's swept area. However, only a fraction of this power can be actually extracted out of the air. If all of air's energy was transferred to the turbine, the air molecules that hit the blades would have to come to a complete stop. This is impossible since for continuous operation the molecules that already hit the blades need to get out of the way to let the air that is behind them hit the blades. If all the air motion was transferred to the blades, the air would pile up in front of the turbine, and then the wind would have to blow around the turbine. In reality, the air that hits the blades must keep some speed to move out of the way to allow continuous air flow into the turbine. According to physics, the theoretical limit of wind energy that can be transferred to the shaft is 59%. This fact is known as the Betz Limit [19]. Therefore, the maximum power extracted from the wind is thus:

$$P = 0.59 \left[ \frac{1}{2} \rho_a A V^3 \right] \quad \text{--- (2.9)}$$

#### **2.2.4. Capacity factor of wind turbines**

Capacity factor is one of the important indices for assessing the field performance of a wind turbine. The capacity factor ( $C_F$ ) of a WECS at a given site is defined as the ratio of the energy actually produced by the system to the energy that could have been produced by it, if the machine would have operated at its rated power throughout the time period. Thus

$$C_F = \frac{E_T}{TP_R} \quad \text{--- (2.10)}$$

The capacity factor reflects how effectively the turbine could harness the energy available in the wind spectra. Hence,  $C_F$  is a function of the turbine as well as wind regime characteristics. Usually the capacity factor is expressed on annual basis. Capacity factor for a reasonably efficient turbine at a potential site may range from 0.25 to 0.40. A capacity factor of 0.4 or higher indicates that the system is interacting with the regime very efficiently [9].

### **2.3. Wind Electric Water Pumping System Components**

#### **2.3.1. Introduction to wind water pumping system**

Different methods for water delivery have been known for many years. The simplest and most economical way is to divert rain or river water by a gravity flow system to the desired location. This method is not applicable in most of the world and it does not operate regularly. Where this is not possible, manual pumping has been the most common method for many years. Their use is essentially for water supply, especially for human consumption and agricultural activities. Wind pump can broadly classified as mechanical systems and electrical systems.

In mechanical wind pumps, the shaft power developed by the rotor is directly used to drive the pump. On the other hand, in electrical wind pumps, wind energy is first converted to electricity, which is then used to energize the pump. Mechanical wind pumps can further be categorized as systems with positive displacement and roto-dynamic pumps. Various types of pumps like the screw pump, piston pump, centrifugal pump, regenerative pump and compressor pump are being used in mechanical wind pumping option. Roto-dynamic pumps mainly the centrifugal are used with the electrical system [9].

Mechanical wind water pumping machines have been used to pump water from wells for centuries. Mechanical wind-pumps are probably the best choice for using wind energy when the annual average wind speed is less than 4m/s. However, it suffers from several important

weaknesses. As a system it requires regular maintenance, not so much for the windmill itself, but for the seals on the pumps. In addition, the mechanical linkage to the pump requires that the windmill should be placed directly over the water source. In some situations this is physically difficult and in others it means that the windmill cannot be placed so as to capture the most wind.

A wind electric pumping system overcomes some of the problems with the mechanical wind water pump systems. This system generates electricity, which, in turn, runs an electric pump. Wind electric pumping systems allow greater siting flexibility, higher efficiency of wind energy conversion, increased water output, increased versatility in use of output power, and decreased maintenance and life-cycle costs.

Although manual pumping has been used widely, moving large volumes of water and/or pumping from deep wells cannot be done effectively with hand pumps, but requires the use of mechanical pumps powered by engines or electric motors. Engine pumps including windmills have traditionally been used to pump water. However, today reliable solar (photo voltaic) and wind turbine pumps are now emerging on the market and are rapidly becoming more attractive than the traditional power sources [3].

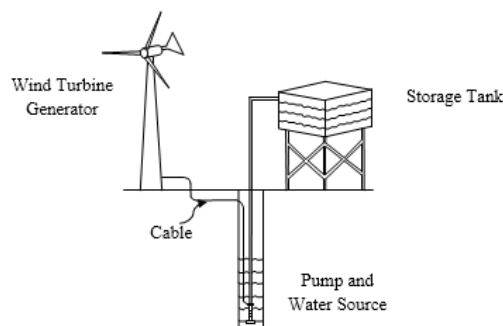


Figure 2.6: General outline of the wind driven water pumping system.

Figure 2.6 shows the outline of most general configuration of the proposed system. It consists of a wind farm with a single wind energy conversion system; a water pumping station with a single motor pump; a water storage system, consisting of a lower and upper reservoir. The advantage of this system configuration is that the wind farm can be located in an area of high wind potential which does not have to coincide with the installation area for the pumping system.

### **2.3.2. Wind turbine generator**

The wind turbine generator unit includes three main components. They are namely the rotor, nacelle, and tower. **Rotor:** the rotor generally consists of two or more fiberglass blades that extend out of the hub. In most turbines, the rotor is mounted to a driveshaft within the nacelle to operate upwind of the tower. In some cases, the rotor is located behind the tower and nacelle. **Nacelle:** the nacelle is a large housing that sits atop the tower behind the rotor. It houses the main mechanical components of the wind turbine: drive train, gearbox, transformer, and generator. **Tower:** the tower supports the nacelle and rotor. Towers are generally made of steel and can be either tubular or lattice [27].

Generally, a wind turbine generator is a machine which converts the power in the wind into electricity. This is in contrast to a ‘windmill’, which is a machine which converts the wind’s power into mechanical power. As electricity generators, wind turbines are connected to some electrical applications. These applications include battery charging circuits, residential scale power systems, isolated or island networks, and large utility grids. Generally, wind energy systems comprise a rotor, a generator or alternator mounted on a frame, a tail, a tower, wiring, and the “balance of system” components: controllers, invertors, and/or batteries [28]. The wind turbines are placed on a tower so that it can access the best wind resource. In most wind turbines, the tower costs more than half of the purchasing cost of wind turbines. Hence, it increases the capital investments. Therefore, the tower is assumed to be manufactured locally which in turn reduces the capital investment and also creates opportunity of income for the local small scale industry.

### **2.3.3. Pump and motor subsystem**

The selection of the pump is based on the pumping head and flow requirement, wind turbine electrical output, and site conditions. Submersible pumps are most commonly used for drilled wells. It is so named because the whole unit, pump and motor are designed to be operated under water. This means the pump does not have to be primed. Once installed and turned on, water flows up the pipe.

The pump end is a multistage (many impellers) centrifugal pump, close coupled to a submersible electric motor. All of the impellers of the multistage submersible rotate in the same direction by a single shaft. Each impeller sits in a bowl and the flow from the impeller is

directed to the next impeller through a diffuser. These three parts (bowl, impeller and diffuser) are known as a stage.

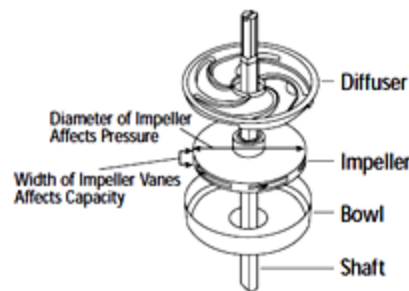


Figure 2.7: Stage of Submersible pump [12].

The capacity of a multistage centrifugal pump (submersible) is largely determined by the width of the impeller and diffuser, regardless of the number of stages. The pressure is determined by the diameter of the impeller, the speed at which it rotates and the number of impellers. The diameter is limited to the size of wells drilled. Most submersibles are designed to fit in four or six inch wells (or larger).

A 372.85watt pump with seven impellers (designed for capacity) would deliver more water at 2.032m than a 372.85watt pump with 15 impellers (designed for pressure) but the latter pump would be able to raise water from a greater depth.

Well water enters the unit through screened openings at the middle of the unit between the pump and motor. There is only one pipe connection which is at the top of the pump. This is the discharge pipe. A check valve is located at the top of the unit to prevent water from the system draining back when the pump isn't running [12].

#### **2.3.4. Storage tank**

This is a tank where the pumped water is stored so that it can be easily accessed for the required application. Now days different types of water storage tanks are available made of either plastic or steel metal. Therefore, based on its capacity, durability and economic advantages it is possible to select for the system.

The design should include an oversized storage tank to help in the event that wind is low for a short period of time. The exact size of the tank should be determined based on the wind intermittency of the site. Inclusion of an emergency storage tank at the location of the well could provide for the community in the event that the wind was low for an extended period.

### **2.3.5. Underground water resource or a well**

The source of underground water or a well is often referred to as shallow or deep. A shallow well is one where the water is within 7.62m of the ground surface. A deep well is where the static water level is more than 7.62m down [12]. There are deep wells (Tula wells) and dispersed springs used to supply water for the society and their cattle's. The deep wells are perhaps the most fundamental feature that has shaped the Borena society, constituting a vital source without which keeping cattle in the Borena ranges would be impossible in the dry season. Tula wells are old, usually much deeper than normal wells comprise the most reliable source of water, never drying up even in the course of sever draughts [21]. The standing water level in a well is called the static head. This is the water level when the pump is not operating. When the pump comes on and is running there often is a change in the water level. This is referred to as drawdown. The drawdown occurs and the water level reaches what is referred to as the pumping level. This is the operating level of the pump.

### **2.4. Wind Energy in Ethiopia**

Wind energy has been used in a variety of ways for water pumping, flour milling and in the last half of the century for electric generation. However, in Ethiopia this technology has begun to be installed not long ago. The EEPCO has gathered data on wind power at four sites, i.e. Mekele, Nazareth, Gondar and Afar, with the support from GTZ. Therefore, large electricity generation system by wind turbines is known to become alternative energy source in Ethiopia. Some 100 wind pumps are operating in the country, providing drinking water for cattle and humans. For instance, in Zuway region alone, 67 such wind pumps provide drinking water for more than 120,000 people [6], which indicates that small scale wind turbines also becoming an increasingly promising way to supply power.

## **2.5. Previous Works on Wind Energy for Water Pumping**

**Árni Vignir Pálmason (2009)** have considered to use a wind powered pumped storage system to ensure secured electricity production from hydropower plant and to reduce construction size of new reservoir in Iceland. Instead of using a wind turbine to generate electric power to drive the pumps, a shaft is proposed to connect the wind turbine and the pumps. Iceland is located at one of the windiest location on Earth. This renewable resource is especially high, both in terms of intensity and consistency. Obviously, using shaft to connect wind turbines and pumps has common problems such as:

- The mechanical linkage to the pump requires that the wind turbines must be placed directly over the water source.
- The system needs regular maintenance; however, in the remote areas there are not as such trained or skilled men to do this action.
- Locations near the well and length of the shaft depends on the location of the pumps and other factors like the landscape.

Considering those points listed above and potential of the site, using wind turbines to produce electricity to drive the pump is better solution. Finally, the thesis indicates the main reasons for non-profitable use of wind pumped storage system are the high cost of powerful (Vestas V80) wind machines and the low electricity sale price. If the analysis is also made by considering medium sized wind turbines, high cost of wind turbine will not be the reason for the system to be profitable [4].

**Brett G. Ziter (2009)** has examined that wind energy pumping is considered an economically competitive, sustainable means of providing water to communities without access to the electricity grid. An analysis conducted using power curve of Bergey Excel-PD (a 10kW wind turbine) shows that there is a significant potential of wind energy for average wind speeds of 5m/s and greater. The basic problem while conducting the analysis was that it does not consider seasonal variations in wind speed. Since the water pumping applications may require year round production and it is important to know the expected output at all times of the year. Finally, using the above relationship, a model has been developed to estimate the output of a system and compared to the performance curve of a Bergey Excel-PD 10kW electric pumping system. The model used for the system, however, is assumed to be more simplified and can be extended to provide more accurate prediction of the system performance. Such extensions can

be made by considering seasonal variation of wind speed for the site and considering different commercially available wind turbines. Most of water pumping applications require year round production of energy and it is important to know the expected output at all times of the year [7].

***Dr. Abdurrahman Al-Ahmari, Dr. Ahmet Bolat, Dr. Ahmet Z. Sahin and Dr. Naif Al-Abbadi, (study and development of wind energy for pumping underground water in the kingdom of Saudi arabia) October, 2006.*** In this project, a detail investigation has been made to determine the feasibility of using wind power for extracting underground water for irrigation purposes in the Kingdom of Saudi Arabia. Several years of recent half-hourly wind speed data collected by KACST at five sites have been used for the analysis. These sites are Dhahran, Gasim, Yanbu, Arar and Dhulom. The feasibility study first has been made using statistical characteristics of both wind speed and wind power density, then the directional characteristics of wind has been determined at each site for underground water pumping.

The power generated from various sizes of wind turbines was calculated at each of the sites using the statistical wind characteristics and the wind turbine characteristics. Then, the underground water pumping capacity at these sites for various sizes of water pumps were determined for varying depths of underground static water level. Average daily water pumping capacities at these sites were obtained on the annual as well as seasonal basis. Next, a number of water pumps that can be operated during the whole year as well as during the various seasons by various wind turbines at these sites were calculated. Finally, economical analysis is done to identify the financial viability of the WEC systems by using currently utilized electric energy operated systems as benchmarks.

From the analysis carried out, it is found that there is a considerable wind power in all the sites for pumping underground water for irrigation purposes. Among the sites considered, Dhulom, Dhahran and Arar exhibited the highest water pumping potential, respectively. This indicates that many remote areas in the Kingdom of Saudi Arabia are suitable for the harnessing of wind energy by using small to mid-size wind energy conversion systems [8].

## Chapter 3: Water Need Assessment and System Sizing

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### 3.1. Water Demand of the Community

Water demand is defined as the volume of water that different categories of consumers can afford to consume in the context of unrestricted access. Therefore, it is the basic step while modeling water pumping system. The parameters used to determine the required amounts of water are volume of water and how far the water is to be transported, thus having the two main criteria the amount of energy needed to pump the water to the required location could be known. In our case, the water would not be transported instead pumped from the lower reservoir to the upper storage tank. Here is some basic needs that should be considered to determine the quantity of water being collected by a wind pumping system:

- Drinking and cooking water supply (for humans and/or livestock),
- Irrigation for rangeland and vegetables production.

Human and livestock water consumption can be estimated by multiplying the daily usage of the total population considered in the system. In most places of Borena, pastoralists settle in communities around the resources of pasture and water consisting of 30-100 households [2]. Based on the 2007 population census by Central Statistical Authority (CSA), each household consist five members of people. In this research, the minimum number of household i.e., 30 in a wereda and average number of different species are considered. Table 3.1 shows the average number of livestock and human population per household for eight woredas in Borena.

Table 3.1: Average number of livestock and human population per household [25].

Wereda	Cattle	Sheep	Goat	Camel	Equine	Population
Dire	23	4	8	3	1	5
Miyo	4	1	1	1	1	5
Teltelle	9	3	5	1	1	5
Yabelo	8	1	4	1	1	5
Arero	14	2	5	2	1	5
Moyale	21	3	8	9	1	5
Bule Hora	6	1	3	1	1	6
Dugda Dawa	24	3	11	1	2	6
<b>Average</b>	14	2	6	2	1	5

When the project comes into reality, the communities enable to produce vegetables for their own consumption. Thereby reducing the expenditures on such items. In other words, the project creates a situation for the communities to participate in small agricultural activities and indirectly earn additional income. In this research, it is assumed that each household is owner of 100m<sup>2</sup> land for vegetable cultivation. That mean each household is capable of cultivating their own vegetable like: cabbage, tomato, onion etc. Table 3.2 illustrates the daily water consumption for different species and irrigation for vegetables.

Table 3.2: Water requirements in liters per day for different species and irrigation [25].

<b>Water demand</b>	<b>Unit</b>	<b>Consumption</b>
Human	l/person/day	15
Cow	l/head/day	15
Camel	l/head/day	18
Sheep	l/head/day	3
Goat	l/head/day	3
Equine	l/head/day	7.5
Irrigation land	l/sq. meter/day	14.5

There is also an important factor, like the amount of water needed by a village while designing a water pumping system, which is the amount of water produced. The water in the well does not always stay at the same level throughout the year. Therefore, a correctly modeling of pumping system should be required in order to keep the amount of water availability throughout the year. However, Tula wells never drying up even in the course of sever draughts so there is nothing to worry about this issue [21].

Based on the average number of population size and water consumption for different needs, the total amount of water consumption per day [ $Q_T$ ] in one of Borena wereda is summarized in Table 3.3 below.

Therefore, to carry out all activities the society needs about 54,075 liters of water per day. This figure indicates that, it is the maximum amount of water needed in the wereda to meet the required activities. Thus, it is very essential to assume constant water consumption throughout the year. However, to account for wastage and seasonal variation of water consumption in the wereda, the total consumption is approximated to 54,500 liters per day.

Table 3.3: Total water consumption of 30 household in a specific wereda.

Water demand	Average number of livestock and population per household	Consumption [L/day]	Consumption [L/Household/Day]
Human	5	15	75
Cow	14	15	210
Camel	2	18	36
Sheep	2	3	6
Goat	6	3	18
Equine	1	7.5	7.5
Irr. Land	100m <sup>2</sup>	14.5/m <sup>2</sup>	1450
<b>Total consumption for the total number of household considered</b>			<b>54075</b>

### 3.2. Water Pumping Power

The pumping (or hydraulic) power required to deliver a volume of water from underground is given by the expression:

$$P_h = \rho_w gQH \quad \text{--- (3.1)}$$

where  $\rho_w$  is the density of water in kg/m<sup>3</sup>,  $g$  is the gravitational acceleration in m/s<sup>2</sup>,  $H$  is the total head in m and  $Q$  is the volume of water in m<sup>3</sup>/s.

The wind pumping system has two main devices namely the pump and wind energy conversion system. These devices are connected and powered electrically with the help of a potential wind resource, so that pumping of water can be take place. The available power of the WECS is obtained from the following equation:

$$P_h = \eta P_{WECS} \quad \text{--- (3.2)}$$

where  $\eta$  is the overall efficiency of the system.

Substituting Eq. (1.4) and Eq. (3.1) in Eq. (3.2), the following formula can be obtained for the amount of water that can be pumped per second:

$$Q = \frac{\eta C_p \rho_a AV^3}{2\rho_w gH} \quad \text{--- (3.3)}$$

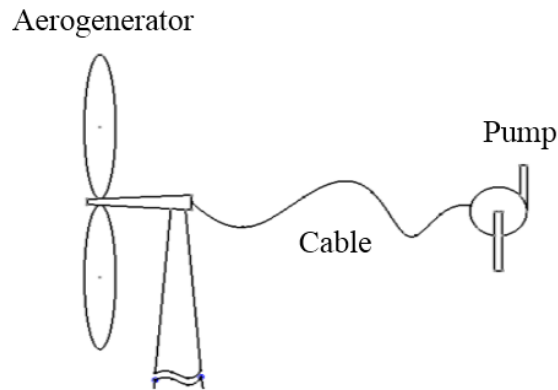


Figure 3.1: Diagram of a wind-electric pump system.

### 3.3. Calculation of Total Dynamic Head Loss

The flow of a fluid in a pipe may be laminar flow or it may be turbulent flow. The flow is laminar if the Reynolds number is less than approximately 2100 to 2300. The flow is turbulent if the Reynolds number is greater than approximately 4000. For Reynolds number between these two limits, the flow may switch between lamina and turbulent conditions. Such flow, represents the onset of turbulent, is called transitional.

The Reynolds number can be calculated using the following expression:

$$R_e = \frac{4\rho Q}{\pi\mu D} \quad \text{--- (3.4)}$$

It is often necessary to determine the head loss,  $h_L$ , that occurs in pipe flow so that the total dynamic head of the system can be known. The overall head loss of the pipe system consists of the head loss due to viscous effects in the straight pipes, termed the major loss and denoted  $h_{L\text{ major}}$ , and the head loss in the various pipe components, termed the minor loss and denoted  $h_{L\text{ minor}}$ . That is,

$$h_L = h_{L\text{ major}} + h_{L\text{ minor}} \quad \text{--- (3.5)}$$

The major head loss is associated with friction (viscous) effects as the fluid flows through the straight pipe and can be expressed as:

$$h_{L\text{ major}} = f \frac{l V^2}{D 2g} \quad \text{--- (3.6)}$$

where  $V$  is the average velocity,  $l$  is the pipe length,  $D$  the pipe diameter,  $g$  is the gravitational acceleration and friction factor. The above equation is called the Darcy-Weisbach equation.

The dimensionless friction factor,  $f$ , is a function of two other dimensionless terms- the Reynolds number based on the pipe diameter and the relative roughness,  $\epsilon/D$ .

For the entire turbulent flow, friction factor can be read from the Moody chart as shown in the Figure 3.2 chart or evaluated using the Colebrook formula which is an empirical fit of the pipe flow data, and expressed as:

$$\frac{1}{\sqrt{f}} = -2.0 \log \left( \frac{\epsilon/D}{3.7} + \frac{2.51}{Re \sqrt{f}} \right) \quad \text{--- (3.7)}$$

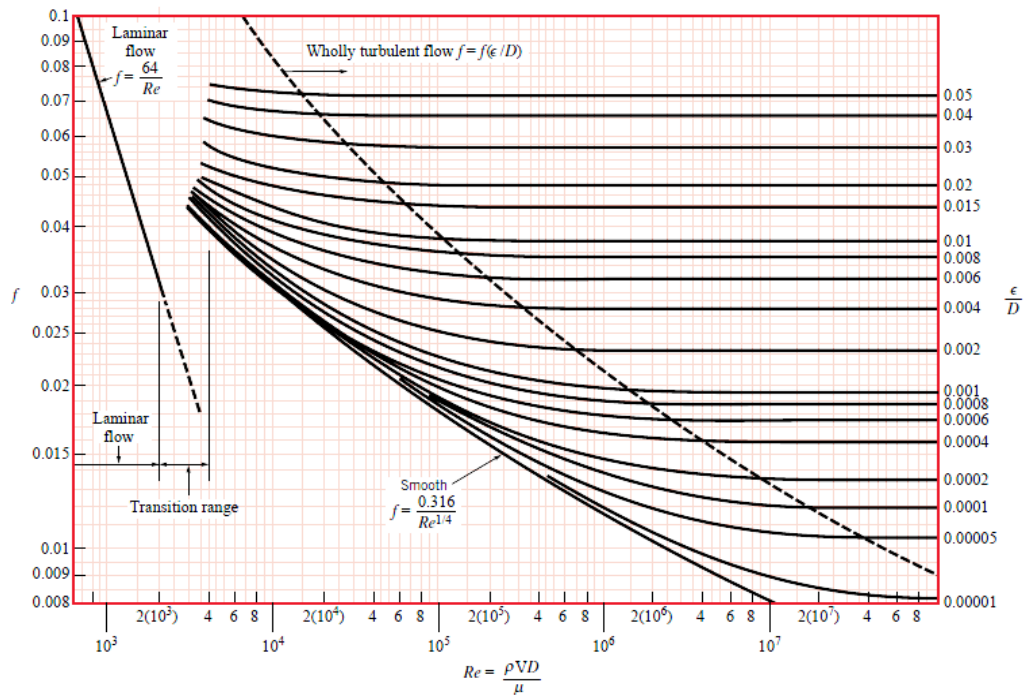


Figure 3.2: The Moody chart [23].

The table shown below is the roughness values,  $\epsilon$ , for various new, clean pipe surfaces.

Table 3.4: Equivalent Roughness for New Pipes [23].

Pipe	Equivalent Roughness, $\epsilon$	
	Feet	Millimeters
Riveted steel	0.003–0.03	0.9–9.0
Concrete	0.001–0.01	0.3–3.0
Wood stave	0.0006–0.003	0.18–0.9
Cast iron	0.00085	0.26
Galvanized iron	0.0005	0.15
Commercial steel or wrought iron	0.00015	0.045
Drawn tubing	0.000005	0.0015
Plastic, glass	0.0 (smooth)	0.0 (smooth)

Losses due to the components of pipe systems (other than the straight pipe itself) are termed minor losses and are given in terms of the dimensionless loss coefficient,  $K_L$ , as:

$$h_{L\text{ minor}} = K_L \frac{V^2}{2g} \quad \text{--- (3.8)}$$

The values of  $K_L$  for such components depend strongly on the shape of the component and only very weakly on the Reynolds number for typical large  $R_e$  flows. Typical values of  $K_L$  for such components are given in Table 3.5.

Table 3.5: Loss Coefficient for Pipe Components [23].

Component	$K_L$	
a. Elbows		
Regular 90°, flanged	0.3	
Regular 90°, threaded	1.5	
Long radius 90°, flanged	0.2	
Long radius 90°, threaded	0.7	
Regular 45°, threaded	0.4	
b. 180° return bends		
180° return bend, flanged	0.2	
180° return bend, threaded	1.5	
c. Tees		
Line flow, flanged	0.2	
Line flow, threaded	0.9	
Branch flow, threaded	2.0	
d. Union, threaded	0.08	
e. Valves		
Globe, fully open	10	
Angle, fully open	2	
Gate, fully open	0.15	
Ball valve, fully open	0.05	

In this case, for a pipe diameter of 2.0in (50.8mm) and water flowing at a rate of 13.62m<sup>3</sup>/hr then the value of Reynolds number would be 94128. Thus, the flow in the pipe is turbulent flow. Water at 20 degree Celsius flowing through a plastic pipe (2.0in in diameter) at a rate of 13.62m<sup>3</sup>/hr. The friction factor for this system can be found either using the Moody's chart or Colebrook formula. A simple iterative solution of this equation gives  $f=0.018219$ .

Now, we are in position to determine the value total dynamic head loss. Substituting all the values and applying Eq. (3.5) and solving  $h_L$ ,

$$h_L = 0.018219 \times \frac{30}{0.0508} \times \frac{2^2}{2 \times 9.81} + (2 + 4 \times 1.5) \times \frac{2^2}{2 \times 9.81} = 3.82\text{m}$$

Then the total dynamic head loss is approximated as,  $h_L = 4.0\text{m}$ .

The total pumping head is the total head required to pump water from the water source to the reservoir; that is, the sum of the static head and friction head. The static head, in case of groundwater from deep-wells, is the static water level plus the drawdown. In our case, these Tula wells are so unique that even in the course of summer they did not exhibit as such a significant drawdown. Therefore, the drawdown can be thought of as negligible. The friction head is the energy loss in pipes and fittings [8 & 19]. Hence, pumping head of the site is approximated as 20m and 4m is considered to be friction losses. Then, the total head for the system would therefore be 24m.

### **3.4. Determination of Pump Size**

Selection of pumps used for water pumping application depends on the daily water requirement, pumping head and type of operation used (position of the pump i.e., inside the fluid media or not). Pumps and motors can be manufactured independently or integrated as a unit. Most submersible pumps are manufactured with their motor to make the operation efficient. In our case the source of water for the system is deep-well and to get access of this resource a submersible pump is a better selection among the others.

One of many producers of pumps is the Goulds pump corporation. The Goulds model VIS vertical turbine pump is shown in Figure 3.3. Using software called ePrism selection of Goulds Pump is so easy [13]. This software is developed to select the required pump size for a specific application. It has two approaches for searching the required pump size namely they are Basic and Advanced. The Basic approach allows the user to enter the operating criteria in order to begin searching for a pump. The later approach allows the user to enter more advanced information relative to his/her requirement. For more information see *Appendix C*.



Figure 3.3: VIS Goulds Vertical Submersible Pump [17].

This research is intended to lift water from a well using wind electric as a power source. The pump is required to deliver 54500 liters of water per day for a head of 24m. Therefore, the pump satisfying the operating criteria can be found using ePrism software.

If the site has a good wind speed resources, wind turbine generator connected with a pump can deliver water in excess to the community. However, the percentage of wind speed exceeding the minimum wind speed needed to run a pump is the main criteria in determining daily operation hours of a pump. Generally, there should be a good wind resources and enough operation time for a pump to deliver the required amounts of water. In some literatures an analysis has been conducted using the performance curve of a wind turbine generator pumping system. The analysis shows that there is significant potential for the use of this technology in locations with average wind speeds of 5m/s and greater. The mean annual wind speed in Borena site at a height of 25m is calculated as 4.8m/s and the percentage of wind speeds exceeding 5m/s is about 3610.3hrs over a year. This means the site could generate electricity, which can run a pump up to 9.9hrs a day. However, the seasonal variation of wind speeds does not allow the system to give uniform electricity output throughout the whole year. For instance, in Borena the maximum percentage of time for wind speed greater than 5m/s is 15.2hrs (in July and August) and the minimum is 4.6hrs a day (in October) [Refer, Table 5.4]. To satisfy communities water demand the system is assumed to operate the whole year delivering the sufficient amounts of water per day. Therefore, to make sure that the wind turbine generator pumping system is running the whole year, one must consider the effect of minimum percentage of time i.e., 4hrs a day.

Hence, according to daily water required and the pump working hours the flow rate should be 60gpm. This is equal to about  $0.0038\text{m}^3/\text{s}$ . The Goulds model VIS vertical turbine pump can pump  $13.625\text{m}^3/\text{hr}$  of water to the height 24m. The power in watt to operate the pump with the total head of 24 m and flow rate of 60gpm is now calculated with Eq. (3.1):

$$P_h = 1000 \times 9.81 \times 24 \times 0.0038 = 891.08\text{W}$$

To pump  $0.0038\text{m}^3/\text{s}$  of water up to a height of 24m, a minimum power of 891.08W is needed. Because the pump is not an ideal machine, the power is divided by the pump efficiency and the shaft power is as follows:

$$P_{\text{shaft}} = \frac{P_h}{\eta_p} \quad \text{--- (3.8)}$$

In the above equation,  $P_{\text{shaft}}$  is the power at the shaft where it connects to the pump,  $P_h$  is the power required to pump water and  $\eta_p$  is the efficiency of the pump. Since the pump and motor sub assembly system exists as a unit, there is no need to estimate the shaft power.

The manufacturers information, calculated from the Goulds software, states that the pump power at 3550RPM is 1.47kW and the efficiency is 60.6%. The efficiency of the pump can also be calculated with Eq. (3.8):

$$\eta_p = \frac{891.08}{1470} = 0.606$$

The calculated pump efficiency is 0.606 or 60.6%. For example, the total hydraulic power required from the wind energy conversion system to drive the pump when pumping 0.0038 m<sup>3</sup>/s of water up to a height of 24m and  $\eta_p = 0.606$ , can now be calculated with Eq. (3.8):

$$P_{\text{WECS}} = \frac{1000 \times 9.81 \times 24 \times 54.5}{0.606 \times 4 \times 3600} = 1470.4W$$

When a pump is operating for 4 hours, it needs an electrical input power of about 5.88kWh a day. Generally, this means that the water pumping system requires an annual average power of 2150kWh. This indicates that a wind machine, which is producing more than the required annual average power, will have a chance to drive the pump.

### **3.5. Technical Specification of Selected WTGs**

Based on the amounts of power required annually and the ranges of capacity factor that a system could have, seven different types and sizes of wind turbine generators are selected to calculate the wind power for the Borena site. These wind machines have been selected according to their application and the rated power output. They range in size from 1 to 3kW. The technical data of the wind machines used for the calculation of wind energy potential of Borena semi-arid area are summarized in Table 3.6.

Table 3.6: Technical specification of seven wind turbine models.

<b>Turbine Type</b>	<b>Cut-in speed [m/s]</b>	<b>Rated output [kW]</b>	<b>Tower height [m]</b>	<b>Rotor diameter [m]</b>
BWCXL.1	2.5	1.0	18 - 29	2.5
Generic 1kW	3.0	1.0	6	3.0
Generic 3kW	3.0	3.0	8	5.0
SkyStream 3.7	3.0	1.8	11 - 33	3.7
WES5 Tulipo	3.0	2.5	6 - 12	5.0
Whisper 200	3.0	1.0	7 - 24	2.7
Whisper 500	3.4	3.0	9 – 21	4.5

NOTE: Power curves of the seven wind machines can be found on *Appendix D*.

## Chapter 4: Wind Resource Assessment of Borena Site

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### 4.1. Wind Speed Data Collected

One of the steps to develop a wind energy project is to assess the area's wind resource and estimate the energy availability. The National Metrology Service Agency (NMSA) has not experienced in estimating the wind energy potential of a site, rather it provides with the necessary data for the process. The National Metrology Services Agency is the main institution for coordinating climate change issues in the country. Among many of the services given by NMSA is providing important and essential data for the achievement of a given project. For this research a large quantity of wind data has been obtained from the Bale Robe Meteorological Branch Office, Negele Station. The data obtained represents magnitude of daily wind speed for six consecutive years from 2004 to 2009 and it is measured at 2 m above the ground. It is found in *Appendix A*.

When assessing the feasibility of a potential wind farm site an indication of the variation of wind speed over an area is required. Therefore, it is clear that the key element of the assessment of energy production for a proposed wind farm site is the prediction of long term wind regime at the site. The raw data obtained is in the form of four digits and to convert it to m/s it have to be multiplied with a factor  $100/(24 \times 3600)$ .

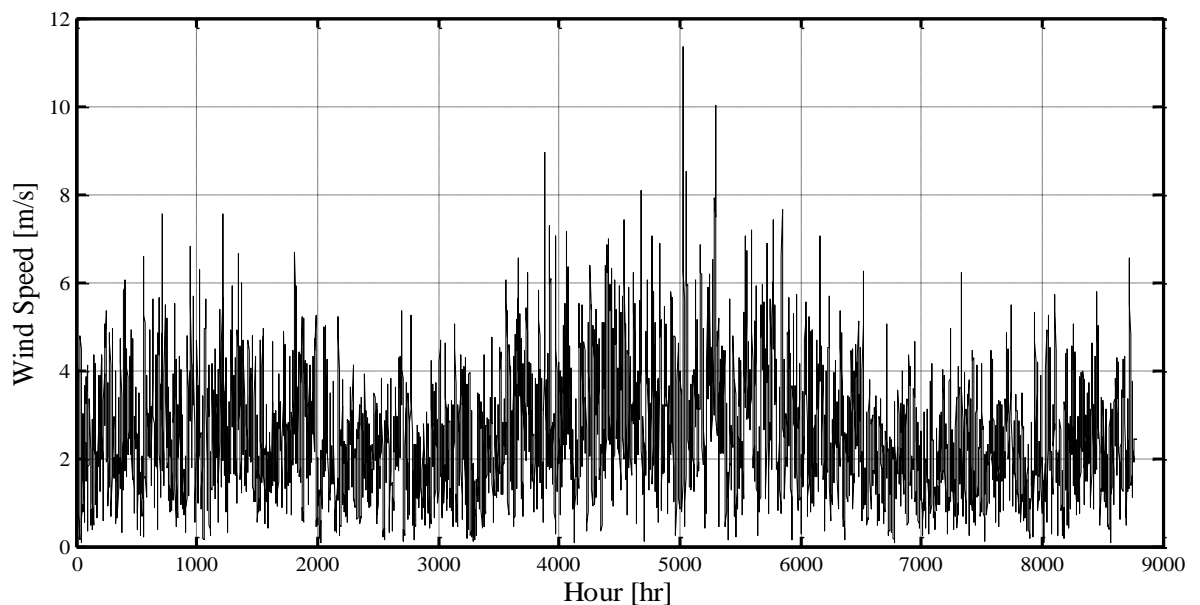


Figure 4.1: Average hourly wind speed for Borena site at 2m.

Therefore, the first task is to convert it to the standard velocity unit i.e., m/s. Next, it needs to be hourly wind speed for accurate estimation of the site, even though it is a long term data. After carrying out these initial steps finally conducting further analysis would be easier. One can find plots of hourly wind speed for each months of a year in *Appendix B*.

Wind resource estimation consists of the determination of the productivity (both maximum energy potential and machine power output) of a given wind turbine at a given site where wind speed information is available in either time series format or in a summary format (average wind speed, standard deviation, etc.)

There are several of ways to summarize the data in a compact form so that one could evaluate the wind resource or wind power production potential of a particular site. Furthermore, some of these techniques can be used with a limited amount of wind data (e.g., average wind speed only) from a given site [19]. In this research, the wind data analysis and resource estimation is done through weibul distribution techniques.

#### **4.2. Direct Use of Wind Speed Data**

Suppose one is given a series of N wind speed observations,  $V_i$ , each averaged over the time interval  $\Delta t$ . These data can be used to calculate the following useful parameters:

The long-term average wind speed,  $V_m$ , over the total period of data collection is:

$$V_m = \frac{1}{N} \sum_{i=1}^N V_i \quad \text{--- (4.1)}$$

Apart from the average wind velocity over the total period of data, its distribution is also a critical factor in wind resource assessment. The basic measure of the unsteadiness of the wind is the standard deviation (or root mean square) of the speed variation. Standard deviation indicates the deviation of individual velocities from the mean value, and it can be expressed as:

$$\sigma_v = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (V_i - V_m)^2} \quad \text{--- (4.2)}$$

Table 4.1 shows the monthly average wind speed values measured at 2m, calculated at 10m and the NASA values for the same location at 10m height.

Table 4.1: Monthly Mean Wind Speed at different Hub Height of Borena [m/s].

Months	Measured at 2 m	Calculated at 10 m	NASA data at 10 m
Jan	2.54	3.80	4.0
Feb	2.66	3.97	3.9
Mar	2.38	3.56	3.4
Apr	1.97	2.95	2.8
May	2.24	3.34	3.4
Jun	2.94	4.40	3.8
Jul	3.35	5.01	4.0
Aug	3.34	5.00	4.0
Sep	2.76	4.13	3.6
Oct	1.87	2.79	2.9
Nov	2.12	3.17	3.1
Dec	2.39	3.57	3.7
<b>Average</b>	2.55	3.81	3.55

Referring to the above table, it has been found that the average wind velocity at 10m has a minimum and maximum value of 2.79 and 5.01m/s respectively. Similarly, the overall mean wind speed of the site is estimated to be 3.81m/s, which is applicable for small scale wind turbines.

Figure 4.2, shown below is the graphical representation of the monthly average wind speed data for the three cases in Table 4.1. From the graph, the three plots follow approximately the same path pattern. Therefore, it can be said that the site has a minimum average wind speed at April & October and a maximum average wind speed at July & August.

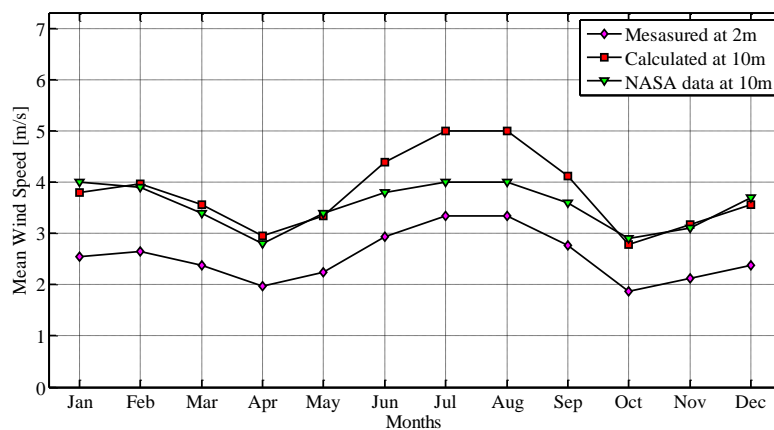


Figure 4.2: Monthly mean wind speed for semi-arid area in Borena.

### **4.3. Description of the Main Program**

The flowchart of the main program is shown in the Figure 4.3, where wind resource characterization and wind energy production by different WTGs have been done while studying the feasibility of Borena's wind resource for small scale water pumping application. First, the hourly and daily wind speed, and turbine power curve data will be loaded. Next, the user is requested to enter the year (2004 to 2009), which he/she wants to analyze and the hub height (10, 15, 20, 25, 30, 35m) from which the results would be evaluated. Finally, the required parameters would be computed numerically and graphically. The data output (results) from the main program are:

- Weibul parameters i.e., the shape and scale parameters,
- Wind power density and wind energy density,
- The most frequent wind speed of the site and percentage of wind speed exceeding  $V_{cin}$
- Annual energy production from seven WTG and the corresponding water output,
- Monthly energy production from Skystream wind turbine and the corresponding water output and
- Daily water output using Skystream power curve and site wind speed.

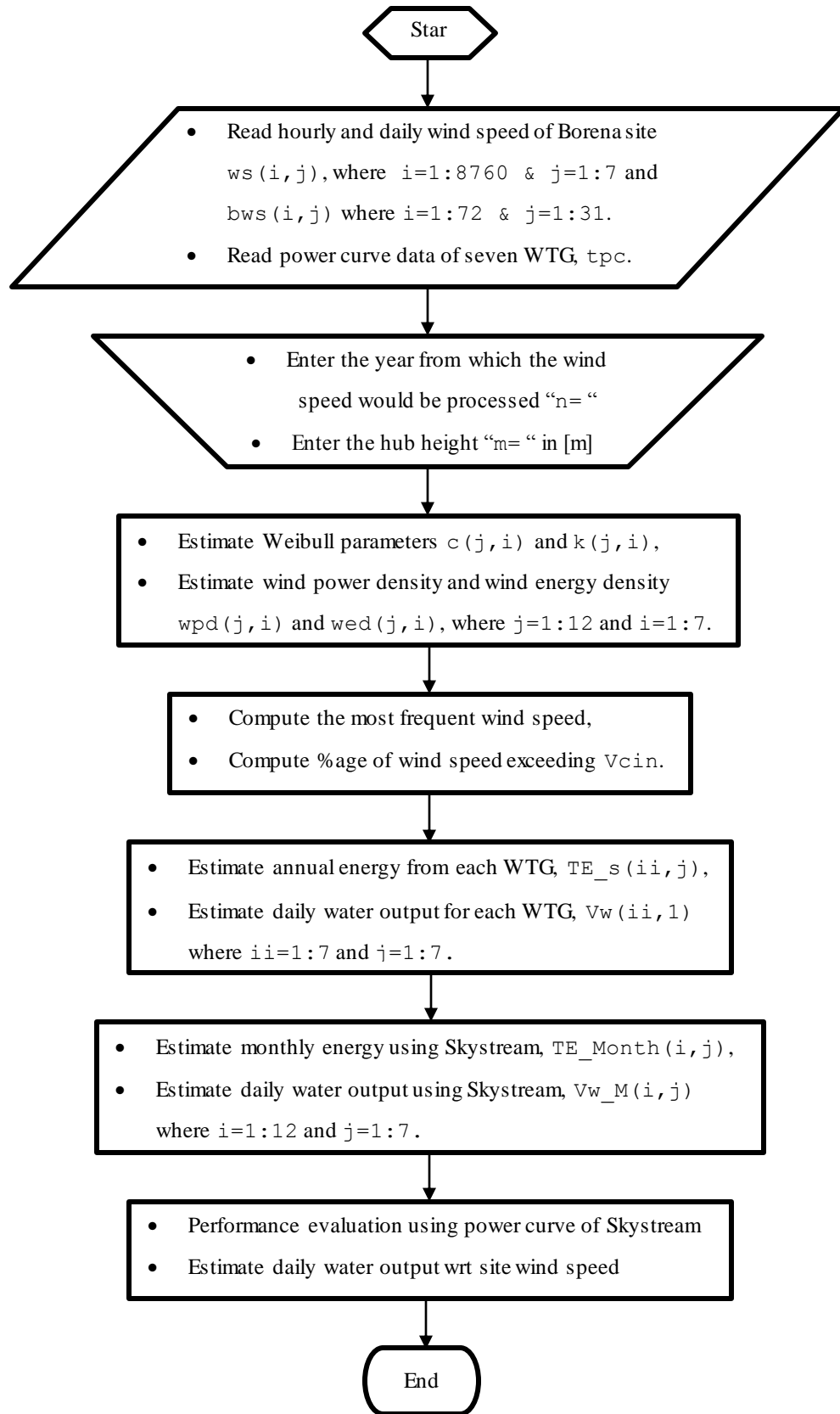


Figure 4.3: Flowchart of the main program using statistical method.

#### **4.4. Statistical Analysis of Wind Data**

Statistical analysis can be used to determine the wind energy potential of a given site and to estimate the wind energy output at this site. If time series measured data are available at the desired location and height, there may be little need for a data analysis in terms of probability distributions and statistical techniques. On the other hand, if projection of measured data from one location to another is required, or when only summary data are available, then there are distinct advantages in the use of analytical representations for the probability distribution of wind speed [19].

The direct method analyzes the data by directly inserting the individual data values into the expressions we are interested in, and finally come up with the end result. However, the statistical technique uses other additional parameters (called shape and scale parameters) to have analyzed the wind data. As a result, the statistical technique is relatively gives better output when compared with direct method. Therefore, an advanced statistical method the so called Weibull distribution is used for analyzing the given wind data.

As hourly data is not available therefore monthly average wind speed has been taken from the given data set. Monthly averaged wind speed data (2004-2009) has been used along with other information of the Borena site (altitude of 1475m asl and ground surface friction factor of 0.25). HOMER synthesized these monthly averaged data based on other parameters such as Weibull factor “k” = 2.2, autocorrelation factor (randomness in wind speed) = 0.9, Diurnal pattern strength (wind speed variation over a day) = 0.25, Hour of peak wind speed = 15 to generate hourly data for a year.

##### **4.4.1. Weibull distribution of wind speed**

It is a matter of common observation that the wind is not steady and in order to calculate the mean power delivered by a wind turbine from its power curve, it is necessary to know the probability density distribution of the wind speed. Various probability functions are fitted with the field data to identify suitable statistical distributions for representing wind systems. The Weibull distribution is normally used to describe the wind variations in a region with an acceptable accuracy level.

In Weibull distribution, the variations in wind velocity are governed by the two basic functions:

- The probability density function, and
- The cumulative distribution function.

The probability density function ( $f(V)$ ) indicates the fraction of time (or probability) for which the wind is at a given velocity  $V$  and is expressed as:

$$f(V) = \frac{k}{c} \left[ \frac{V}{c} \right]^{k-1} e^{-(V/c)^k} \quad \text{--- (4.7)}$$

where,  $k$  is the Weibull shape factor and  $c$  is scale factor.

The higher the value of the shape factor (from 1 to 3) the higher the median wind speed. The cumulative distribution function of the velocity  $V$  indicates the fraction of time (or probability) that the wind velocity is equal or lower than  $V_m$ . Then the cumulative distribution  $F(V)$  is the integral of the probability density function. Thus,

$$F(V) = \int_0^{\infty} f(V)dV = 1 - e^{-(V/c)^k} \quad \text{--- (4.8)}$$

The average wind velocity of a region, following the Weibull distribution, is given by:

$$V_m = \int_0^{\infty} V f(V)dV \quad \text{--- (4.9)}$$

Substituting for  $f(V)$ , rearranging and finally introducing the standard gamma ( $\Gamma$ ) function, the average wind velocity is expressed as:

$$V_m = c\Gamma\left(1 + \frac{1}{k}\right) \quad \text{--- (4.10)}$$

The standard deviation of wind velocity, following the Weibull distribution is:

$$\sigma_V = c \left[ \sqrt{\Gamma\left(1 + \frac{2}{k}\right) - \Gamma^2\left(1 + \frac{1}{k}\right)} \right] \quad \text{--- (4.11)}$$

Under the Weibull distribution, the major factor determining the uniformity of wind is the shape factor  $k$ . For analyzing a wind system following the Weibull distribution, the Weibull parameters  $k$  and  $c$  must be estimated.

It is not a straightforward process to get  $c$  and  $k$  in terms of  $V_m$  and  $\sigma_v$ . However, there are a number of methods that can be used. In this case, I have selected the Analytical or Empirical that is good for  $1 \leq k \leq 10$  [19].

Considering the expressions for average velocity and standard deviation given in Eq. (4.1) and Eq. (4.2), the shape factor  $k$  can be easily obtained. The simplest way of doing this is through a simple curve fitting procedure. A good fit to the relation which is indistinguishable from the exact relationship on the scale of the above graph is:

$$k = \left( \frac{\sigma_v}{V_m} \right)^{-1.086} \quad \text{--- (4.12)}$$

Using the values in Table 4.1 in to the above equation monthly basis shape factor can be calculated. By doing so, the average value of this parameter is found to be  $k=2.18$ . Clearly, this is a good site on which to position a wind turbine. If the value of the shape factor is approximated to  $k=2.0$ , it will have an error of order 9%. This implies that applying the Rayleigh distribution to the wind data analysis would not have a significant change on the result. And the expression for the scale factor  $c$  is as follows:

$$c = \frac{V_m}{\Gamma\left(1 + \frac{1}{k}\right)} \quad \text{--- (4.13)}$$

Based on statistical method, the shape and scale parameters are determined by using MATLAB R7.12 software. There is a syntax named “`parmhat = wblfit(data)`”, which returns the maximum likelihood estimates of the parameters of the Weibull distribution given the values in the vector data. `parmhat` is a two-element row vector: `parmhat(1)` estimates the Weibull parameter  $c$ , and `parmhat(2)` estimates the Weibull parameters  $k$ , in the probability density function [MATLAB Help].

$$y = f(x|c, k) = kc^{-k}x^{k-1}e^{-\left(\frac{x}{c}\right)^k} I_{(0,\infty)}(x) \quad \text{--- (4.14)}$$

Following the Weibull Distribution method the values of mean wind speed ( $V_m$ ), standard deviation ( $\sigma_v$ ), shape ( $k$ ) and scale ( $c$ ) factors on monthly basis can be seen in the table below. From the table, maximum and minimum mean wind speeds are appeared on July and October respectively. As a result, the values obtained in Table 4.2 follows approximately the same path pattern as in the Figure 4.2 too.

Table 4.2: Monthly distribution parameters of Borena at 10m.

Months	$V_m$ [m/s]	$\sigma_v$ [m/s]	$c$ [m/s]	$k$
Jan	3.80	1.84	4.29	2.18
Feb	3.98	1.90	4.49	2.21
Mar	3.54	1.74	4.00	2.15
Apr	2.92	1.39	3.30	2.23
May	3.37	1.63	3.81	2.18
Jun	4.41	2.13	4.98	2.18
Jul	5.02	2.41	5.67	2.21
Aug	5.07	2.47	5.72	2.16
Sep	4.02	1.91	4.53	2.22
Oct	2.80	1.35	3.16	2.18
Nov	3.20	1.55	3.61	2.18
Dec	3.55	1.71	4.00	2.18
Average	3.80	1.84	4.29	2.18

Now the probability density function that best describes the Borena site can be calculated with the application of Eq. (4.7). The following figure shown below illustrates the probability and cumulative distribution of wind speed of the Borena site.

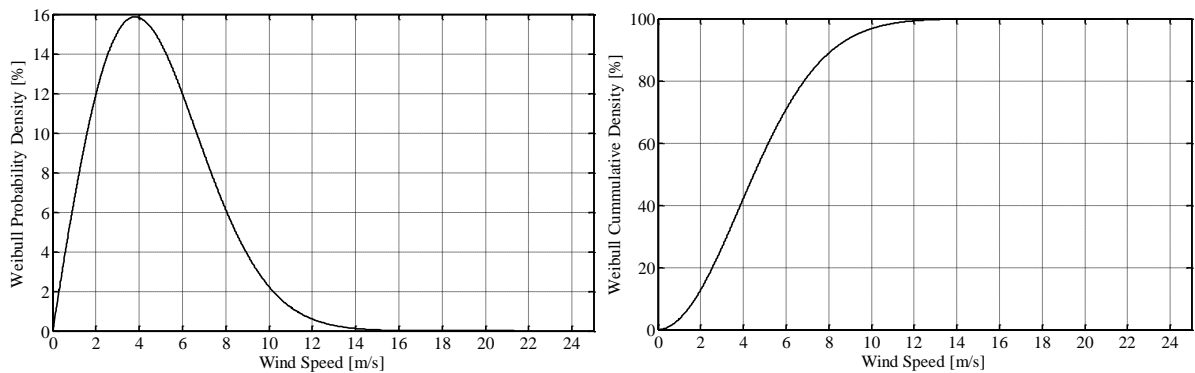


Figure 4.4: Weibull Probability and Cumulative Density Function of Borena at 25m.

The probability density and cumulative functions of a wind regime, following the Weibull distribution are shown in Figure 4.5. The shape and scale parameter values for this site are 2.2 and 5.4m/s respectively. The peak of the probability density curve indicates the most frequent wind velocity in the regime. From the probability density curve, it can be said that the most frequent wind speed value is about 3.8m/s at a height of 25m above the surface of the ground.

The cumulative distribution function can be used for estimating the time for which wind is within a certain velocity interval. Probability of wind velocity being between  $V_1$  and  $V_2$  is given by the difference of cumulative probabilities corresponding to  $V_1$  and  $V_2$ . Thus,

$$P(V_1 < V < V_2) = F(V_2) - F(V_1) \quad \text{--- (4.15)}$$

That is

$$P(V_1 < V < V_2) = e^{-[V_1/c]^k} - e^{-[V_2/c]^k} \quad \text{--- (4.16)}$$

We may be interested to know the possibilities of extreme wind at a potential location, so that the system can be designed to sustain the maximum probable loads. The probability for wind exceeding  $V_x$  in its velocity is given by [9]:

$$P(V > V_x) = 1 - \left[ 1 - e^{-[V_x/c]^k} \right] = e^{-[V_x/c]^k} \quad \text{--- (4.17)}$$

In our case, the wind turbines selected for the analysis have a cut-in velocity 3m/s. Therefore, by using Eq. (4.17) the probability for wind speed exceeding the cut-in velocity is 75.9%, which means that the Borena site has a potential wind speed for 6648 hours per year (8760 hours) at 25m above the ground. This indicates that the wind machines can produce power for almost 75.9% of the time during the year. If it is assumed that there is a constant wind power throughout the year, then the site has a potential of producing useful power for 18hr a day. Therefore, the pump can operate and deliver the required amount of water every day, because the pump is assumed to run 4hrs a day.

#### **4.4.2. Resource estimation**

##### ***I. Resource characterization***

After the wind probability density has been determined, the wind power density for each wind velocity of the site can be expressed as follows:

$$\frac{P_{av}}{A} = \frac{1}{2} \rho \sum_{i=1}^n f(V) V_i^3 \quad \text{--- (4.18)}$$

where  $n$  is the number of wind speed readings,  $\rho$  is the air density ( $\text{kg/m}^3$ ),  $V_i^3$  is the cube of the  $i^{\text{th}}$  wind speed (m/s) value.

Monthly variation of the mean wind power density calculated at height of 10m is shown in Figure 4.5. At 10m the maximum mean WPD of  $80.2\text{W/m}^2$  occurred during the month of August while the minimum mean WPD of  $13.3\text{W/m}^2$  occurred during the month of October.

Referring to Table 2.2, one can see that wind class 1 at 10m has WPD values between 0 and 100W/m<sup>2</sup>. Therefore, the semi-arid area of Borena belongs to *wind power class 1*.

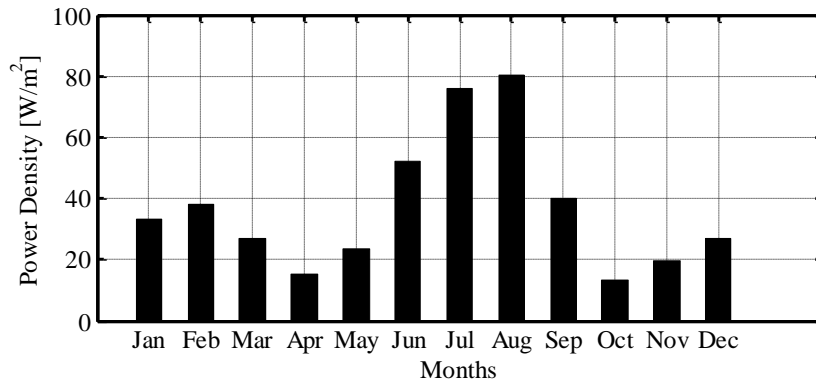


Figure 4.5: Monthly average power density of Borena at 10m.

Once wind power density of a site is given, the wind energy density for a desired duration, T, can be calculated as:

$$\frac{E_{av}}{A} = \frac{1}{2} \rho \Delta t \sum_{i=1}^n f(V) V^3_i \quad \text{--- (4.19)}$$

Eq. (4.19) can be used to calculate the available wind energy for any defined period of time and probability distribution of wind speed in Borena site. Thus, monthly variation of the mean wind energy distribution calculated at height of 10m is shown in Figure 4.6. The maximum mean WED of 59.67kWh/m<sup>2</sup> occurred during the month of August whereas the minimum mean WED of 9.90kWh/m<sup>2</sup> occurred during the month of October. The average wind power density at 10m is estimated to be 27.16kWh/m<sup>2</sup>.

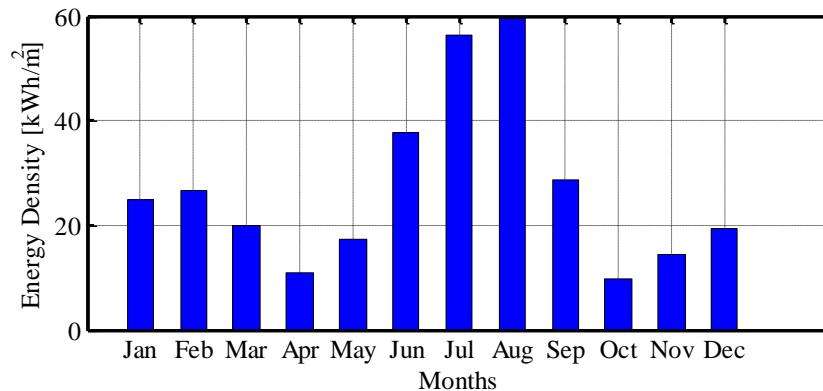


Figure 4.6: Monthly average energy density of Borena at 10m.

The potential of wind power generation in Borena site at 10m and 25m hub height can be summarized in the table below.

Table 4.3: Wind power and energy density of Borena estimated at 10m and 25m.

Months	@ 10m hub height		@ 25m hub height	
	$P_{av}/A$ [W/m <sup>2</sup> ]	$E_{av}/A$ [kWh/m <sup>2</sup> ]	$P_{av}/A$ [W/m <sup>2</sup> ]	$E_{av}/A$ [kWh/m <sup>2</sup> ]
Jan	33.31	24.78	66.23	49.27
Feb	38.11	26.53	75.78	52.74
Mar	26.94	20.04	53.56	39.85
Apr	15.32	11.03	30.46	21.93
May	23.47	17.46	46.67	34.72
Jun	52.20	37.58	103.79	74.73
Jul	75.79	56.38	150.67	112.10
Aug	80.20	59.67	159.45	118.63
Sep	40.02	28.81	79.57	57.29
Oct	13.30	9.90	26.44	19.67
Nov	19.83	14.28	39.42	28.38
Dec	27.01	19.45	53.70	38.67

**II. Energy production by wind turbine generator**

The power that can be generated from a wind machine was obtained using the wind power characteristics of the wind machine and the wind duration data. The following expression is used to find the average wind machine power:

$$P_{av} = \sum_{i=1}^N \left\{ \exp \left[ - \left( \frac{V_i}{c} \right) \right] - \exp \left[ - \left( \frac{V_{i+1}}{c} \right) \right] \right\} P_w \left( \frac{V_i + V_{i+1}}{2} \right) \quad \text{--- (4.20)}$$

Annual average power generation at Borena site for seven different sizes of wind turbine at different wind speed is shown in Table 4.4. The table shows the approximate energy that can be generated annually from small wind turbine generators at 25m of hub height.

Table 4.4: Energy Production at 25m hub height using statistical method.

Wind Turbine Type	Average Energy [kWh]
BWCXL.1	1708.75
Generic1kW	991.84
Generic3kw	2974.40
SkyStream 3.7	3486.74
WES5 Tulipo	6345.91
Whisper 200	1879.07
Whisper 500	5828.36

## Chapter 5: Wind Turbine Generator Selection and System Design

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### 5.1. Technical Assessment of WTG

The wind turbine generator is the main component in wind electric water pumping system, which is responsible for electric generation to power the pump. To meet the communities water demand the system should be capable of producing enough amounts of electrical energy. Thus, a wind turbine generator interacting efficiently with the site and relatively cheaper one would be selected as the system component. As mentioned above, the main criteria for choosing the most suitable WTG is according to which WTG gives maximum capacity factor and low purchasing cost.

Table 5.1: Annual energy harnessed and  $C_F$  at 25m hub height using statistical method.

Wind Turbine Type	Average Energy [kWh]	Capacity Factor ( $C_F$ )
BWCXL.1	1708.75	0.20
Generic1kW	991.84	0.11
Generic3kw	2974.40	0.11
SkyStream 3.7	3486.74	0.22
WES5 Tulipo	6345.91	0.29
Whisper 200	1879.07	0.21
Whisper 500	5828.36	0.22

Table 5.1 shows the annual energy yield and the capacity factor at 25m for seven different wind turbines in Borena site. *WES5 Tulipo* is the one, which can generate the maximum annual wind energy of 6345.91kWh followed by *Whisper 500* and *SkyStream 3.7* respectively. On the other hand *Generic 1kW* generates the minimum annual wind energy of 991.84kWh. Generic 1kW and Generic 3kW has the least capacity factor of 0.11, which indicates that these wind turbines are not efficient in the Borena site.

The wind energy conversion system should produce a minimum of 5.88kWh per day and 2150kWh annually to drive the pump so that delivering the required amounts of water is possible. Analysis of the wind power potential of Borena site showed that among the seven wind turbines chosen for the analysis, only four seems to satisfy the requirement. Namely, they are *Generic 3kW*, *SkyStream 3.7*, *Whisper 500* and *WES5 Tulipo*. The average daily yield of

water for each wind turbine pump system at the Borena site is given in Figure 5.1 for total dynamic head of 24m and 60.6% conversion efficiency.

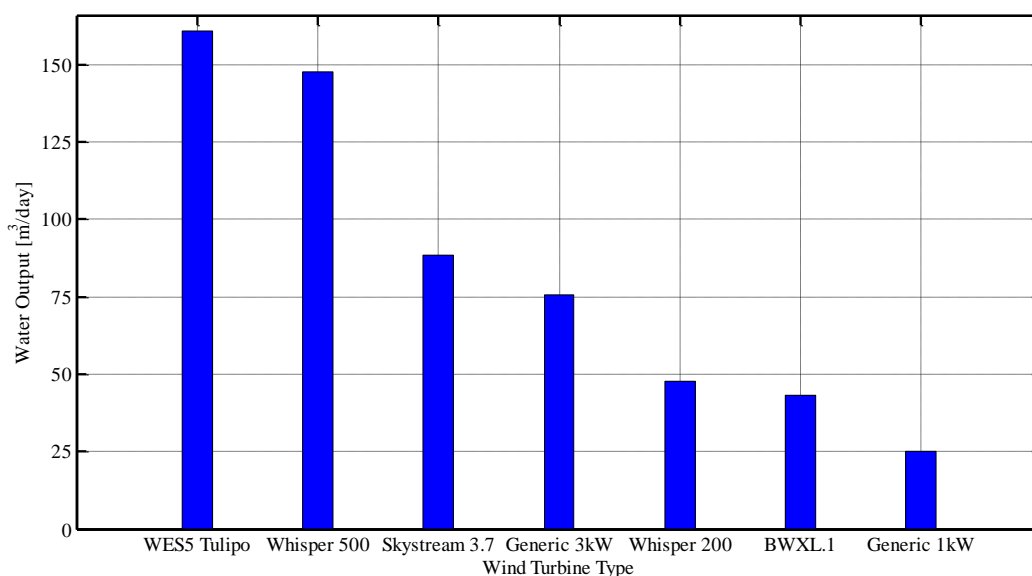


Figure 5.1: Average daily water flow rate for different wind turbines.

Considering the above figure the first four wind turbines can deliver water more than 54.5 cubic meters per day. This indicates that the three wind machines are in agreement with the site daily water requirement. Since the capacity factor of *Generic 3kW* is extremely less than the reasonable value, we have left only with three wind turbines that are relatively very efficiently interacting with the site. Therefore, the most efficient and economical wind turbine for the Borena site is going to be selected from these wind turbines.

## 5.2. Economic Assessment of WTG

The investment costs while estimating wind project consist of purchasing the wind turbine, cost of tower, the cost of land, controls, civil works, the installation charges and other costs (road, permits etc.). However, in this feasibility study the main objective is to select a single wind turbine by comparing their efficiency and economic aspects of the product for Borena site. The costs apart from wind turbine cost are assumed to have same effect in the analysis for each turbine. Therefore, the initial cost (investment cost) of the project is assumed to include only cost of the wind turbine.

Some components of the wind machine are prone to wear and tear due to continuous operation; examples are gearboxes and transmission elements. Extreme aerodynamic loading may cause

fatigue to the rotor blades and the climatic factors may also affect the degree of maintenance required for the system. As a result, wind turbines require periodic attention and proper maintenance for trouble free operation. Considering these factors, it is a usual practice to consider the operation and maintenance charges as a fraction of the capital cost of the system. It logical to assign that 1.5 to 2 per cent of the system cost for yearly repair and maintenance [9]. The incomes are the amounts of electricity generated and by product from small agricultural activities.

Table 5.2: Technical specifications and costs for three different wind turbines.

	<b>SkyStream</b>	<b>WES5 Tulipo</b>	<b>Whisper 500</b>
<b>Rated power</b> [kW]	1.8	2.5	3.0
<b>Rotor diameter</b> [m]	3.7	5.0	4.5
<b>Annual Energy</b> [kWh]	3486.74	6345.91	5828.36
<b>Investment cost</b> [\$]	5035	7830	7950
<b>O&amp;M cost</b> [\$/yr]	100.70	156.60	159.00

Table 5.2 illustrates the technical specifications for the chosen wind turbines, with the aim to give a clear picture over the main characteristics and also make it easy to compare them against each other.

There are a number of different calculation methods and theories when it comes to evaluating if a product or investment is profitable or not. In this paper the net present value and internal rate of return methods are used for calculating the payback period and possible profits [1].

### **5.2.1. Net present value**

The net present value (NVP) is the net value of all benefits (cash inflows) and costs (cash outflows) of the project, discounted back to the beginning of the investment. The benefits will essentially include the income from sale of electricity generated. If this system is installed, it creates a situation for the young men to participate in a small agricultural activities rather than wasting their time in lifting water from the well. Consequently, this is also additional income obtained from the byproduct of the agricultural activities. The capital investment and the accumulated value of annual operation and maintenance costs constituting the payments. Thus the net present value is given by:

$$NPV = B_A \left\{ \frac{[1+r]^n - 1}{r[1+r]^n} \right\} - C_I \left\{ 1 + m \left( \frac{[1+r]^n - 1}{r[1+r]^n} \right) \right\} \quad \text{--- (5.1)}$$

where NPV is net present value,  $B_A$  is annual benefit,  $C_I$  is the capital investment,  $n$  is the expected life,  $r$  is real rate of interest and  $m$  is the maintenance cost factor.

$$B_A = E_A P_e + I_A \quad \text{--- (5.2)}$$

where  $E_A$  is the annual energy production (kWh/year),  $P_e$  is the price obtained for electricity (ETB/kWh) and  $I_A$  is income from small agricultural activities. Thus, the simple payback period is given by:

If the benefits  $B_A$  and cost  $C$  is inflated at annual rate  $i$ , the benefit  $B_{A,j}$  and cost  $C_j$  in year  $j$  becomes:

$$B_{A,j} = B_A [1+i]^j \quad \text{and} \quad C_j = C [1+i]^j \quad \text{--- (5.3)}$$

Thus, the net present value, NPV, becomes:

$$NPV = B_A \left\{ \frac{[1+i]([1+r]^n - [1+i]^n)}{[1+r]^n [r-i]} \right\} - C_I \left\{ 1 + m \left( \frac{[1+i]([1+r]^n - [1+i]^n)}{[1+r]^n [r-i]} \right) \right\} \quad \text{--- (5.4)}$$

If the NPV is greater than 0, the project is economically acceptable as it will bring profit to the investor. While comparing investment options which are mutually exclusive, the project with higher NPV should be selected [9].

The payback period of the investment can be found by equating Eq. (5.4) to zero and solving for  $n$ . payback period is the period of time required to recoup an initial investment. In its simplest form, it is expressed in equation form as:

$$PP = \frac{\ln \left\{ \left[ (1+i) - \left( \frac{C_I}{B_A - m C_I} \right) (r-i) \right] / (1+i) \right\}}{\ln [(1+i)/(1+r)]} \quad \text{--- (5.5)}$$

### 5.2.2. Internal rate of return

The internal rate of return (IRR) is defined as the discount rate at which the accumulated present value of all the costs becomes equal to that of the benefits. In other words, with IRR as the discount rate, the net present value of a project is zero. The IRR is often used by utilities or business in assessing investments and is a measure of profitability. The higher the IRR, the better the economic performance of the wind energy system in question [19].

$$IRR = \text{Values of discount rate for NPVs to equal zero} \quad \text{--- (5.6)}$$

### 5.2.3. Economic Comparison of Wind Turbines

I have assumed that the lifetime of the wind turbine is 20 years and decided to use a real rate of interest of 8%. This results in a net present value factor of 9.82. The electricity price is estimated according to the Ethiopian Electric Power Corporation tariff. The electricity price can be calculated by first determining in what specific Block ID is the system belongs (See *Appendix A*). The basic assumption here is that the electricity generated by the wind turbine is used to replace electricity from the grid. Assume that the income from agricultural activities from the whole societies is around 50ETB per day.

Table 5.3 illustrates a basic comparison of the economic based on Table 5.2. The combinations that are feasible from an economic point of view are marked light green in the table. The main results are that SkyStream 3.7 seems to be more profitable than both WES5 Tulipo and Whisper 500.

Table 5.3: Economic comparison of the three wind turbines.

	<b>SkyStream 3.7</b>	<b>Whisper 500</b>	<b>WES5 Tulipo</b>
Investment cost [\$]	5035	7830	7950
Annual production[kWh]	3869.1	6451.9	6971.9
Payback period [years]	6.731	12.50	11.76
NPV [\$]	4746.8	2156.2	2498.0
IRR	0.192	0.115	0.121

The payback periods vary from 6.731 years (*SkyStream 3.7*) to about 12.50 years (*Whisper 500*). The net present method results a positive value for the three wind turbines, and the *SkyStream 3.7* has the maximum income at the 20<sup>th</sup> year. Similarly, the internal rate of return is higher than the assumed real interest rate i.e., 8%. Therefore, these aero-generators are applicable regarding their profitability. However, considering those criteria the *SkyStream 3.7* is the best among the rest two wind turbine generators. Figure 5.2 illustrates the net present value and payback period of *SkyStream 3.7* for the allocated time period, i.e., from 2012 to 2032.

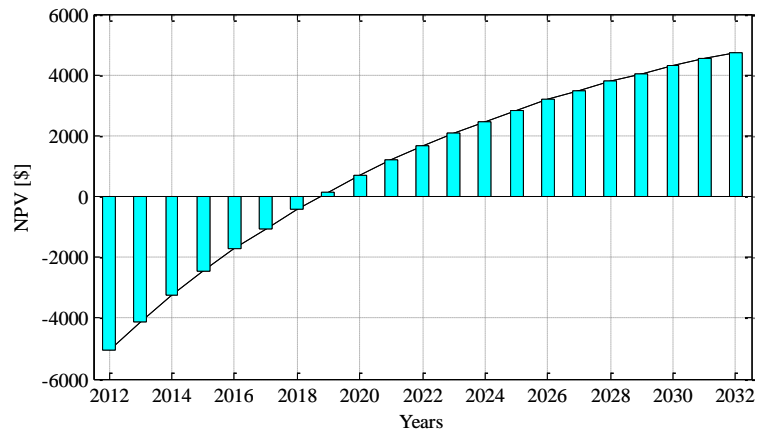


Figure 5.2: Net present value and payback period of *SkyStream 3.7*.

### 5.3. Wind Electric Water Pumping System Design

The wind electric system is used to pump water from deep wells (Tula) to a reservoir where water is collected and accessed easily for different applications. This would enhance the community's productivity and helps them to earn additional income. Thus, to meet their living standards, the wind data for Borena have been used for designing the pumping system and are shown in Table 5.4. The mean annual wind speed between 2004 and 2009 is 4.8m/s at 25m and the wind speed availability for wind speed greater than 5m/s, is 41.2%. The following basic criteria have been applied in designing the wind water pumping system:

- Wind speed data at 25m height above the ground,
- 25m wind turbine generator tower height,
- 20m static water head and 4m friction head, giving a total head of 24m,
- Daily water requirement of 54.5m<sup>3</sup> and
- The pump is running 4hrs a day.

Using the above design criteria, a *SkyStream 3.7* wind turbine generator having 1.8kW rated power was selected. The performance specifications of the wind pumping system are shown in Figure 5.3. The pump selection procedure was based on the software called ePrism by Goulds pump manufacturer's company and the pump model VIS is selected. The system is designed so as to connect the pump directly to the wind generator through a cable. The estimated water output from the system is expected to meet the communities demand. However, in April and October there could be insufficient of water. The balance then has to be met by providing additional reservoir, which can hold the extra amount of water in the neighboring months.

Table 5.4: Monthly and yearly wind availability at Borena, 2004-2009.

Years	Percentage of time for wind speed exceeding 5m/s							No. of hours per month	Avg. no. of hours per day
	2004	2005	2006	2007	2008	2009	%		
<b>Jan</b>	39.7	36.3	50.2	40.4	50.8	38.7	42.7	317.6	10.2
<b>Feb</b>	47.0	46.2	43.3	43.8	52.4	46.7	46.6	317.0	11.3
<b>Mar</b>	41.4	36.5	27.8	39.6	36.8	39.2	36.9	274.5	8.9
<b>Apr</b>	17.9	27.4	18.7	22.8	23.9	22.4	22.2	159.6	5.3
<b>May</b>	34.9	24.7	24.8	35.0	48.1	29.6	32.9	244.4	7.9
<b>Jun</b>	55.0	50.2	58.8	58.2	58.8	44.5	54.3	390.7	13.0
<b>Jul</b>	68.6	63.7	60.5	55.7	69.5	60.7	63.1	469.7	15.2
<b>Aug</b>	67.9	59.6	61.7	60.3	67.4	63.7	63.5	472.1	15.2
<b>Sep</b>	42.7	52.4	49.5	52.2	44.4	42.4	47.3	340.3	11.3
<b>Oct</b>	31.4	16.2	14.8	15.4	15.8	21.4	19.2	142.5	4.6
<b>Nov</b>	25.3	28.2	24.0	38.3	27.4	30.1	28.9	208.1	6.9
<b>Dec</b>	37.8	49.6	29.5	47.9	31.1	24.9	36.8	273.8	8.8
<i>Mean = 41.2%</i>							<i>Total = 3610.3hrs</i>		

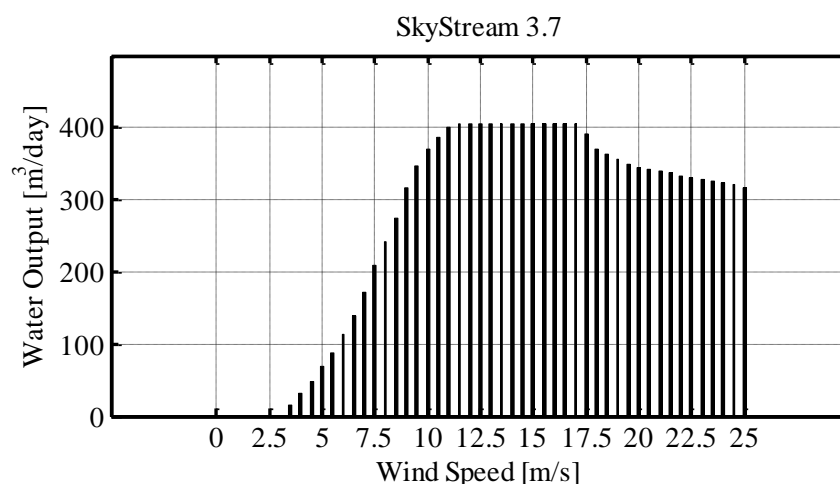


Figure 5.3: Performance of the pumping system (SkyStream 3.7 and VIS Goulds Pump).

The figures shown below displays the monthly water output of the system in Borena site. It is clearly seen that water demand of the community is satisfied for all months except in April and October. The minimum water requirement in the community is 54.5m<sup>3</sup>/day, but in both months i.e., April and October the system cannot deliver such amounts of water. This will require another means of getting water to meet the community's demand.

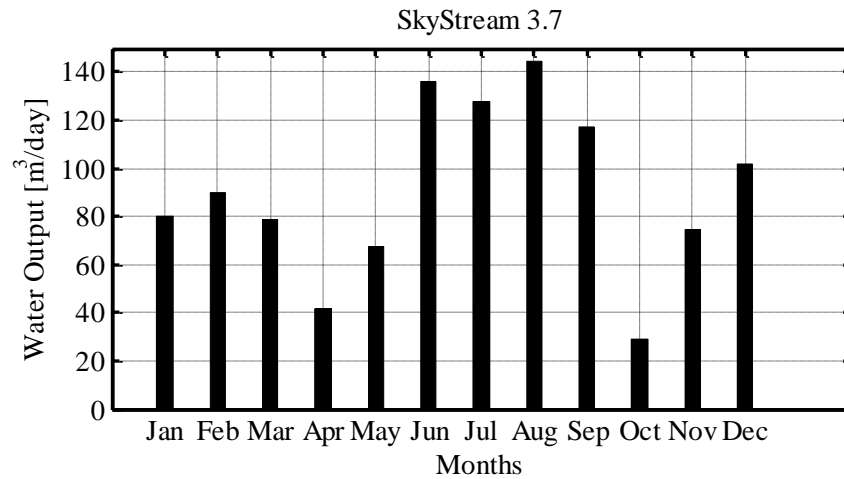


Figure 5.4: Daily water output in each month.

However, the amounts of water output for the rest of months is more than enough, in other words the system can give water in excess of the required amount. Therefore, in order to utilize the system independently, providing additional reservoir solves the problem that could be created in April and October. So, the system can stand by itself for the whole year serving the community.

## Chapter 6: Results and Discussion

This research is focused on studying the feasibility of implementing wind turbine generator for water pumping application in Borena zone. The wind speed data has been analyzed using MATLAB R7.12 software and the results are summarized accordingly.

### 6.1. Energy Harnessed by Wind Turbine Generators

Annual average power generation at Borena site for seven different sizes of wind turbine at different wind speed is plotted in Figure 6.1 and the numerical values are shown in Table 4.4. The figure indicates that the approximate energy that can be generated annually from small scale turbines at 25m of hub height. It has been calculated for equal interval of wind speed from 0 up to 25m/s with even increments of 0.5m/s. Observing the annual energy produced, *WES5 Tulipo* give the maximum output of all the rest wind turbines. The wind machines are generating energy for wind speed from 3m/s to 15m/s and this indicates that the probability distribution of wind speed above 15m/s is about zero.

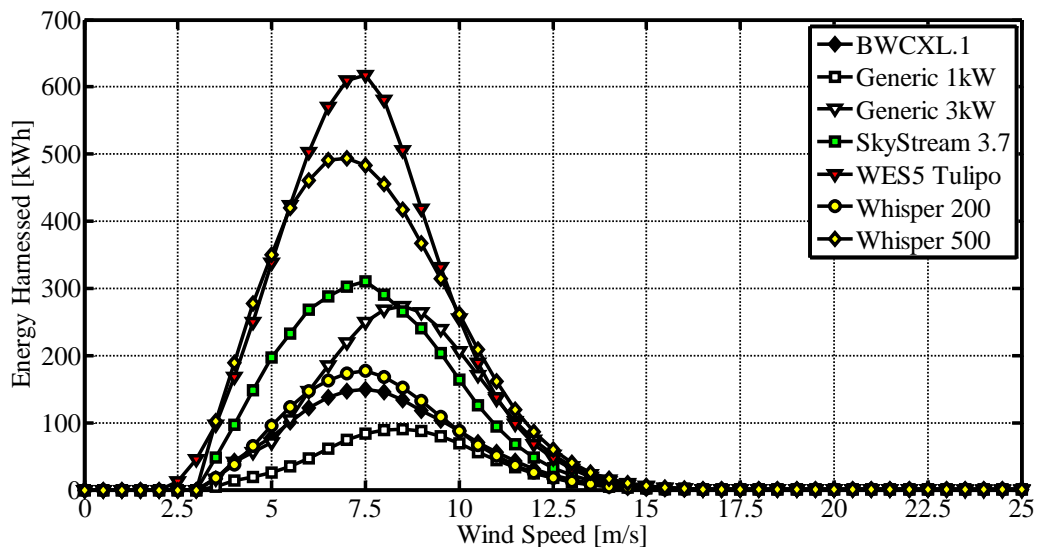


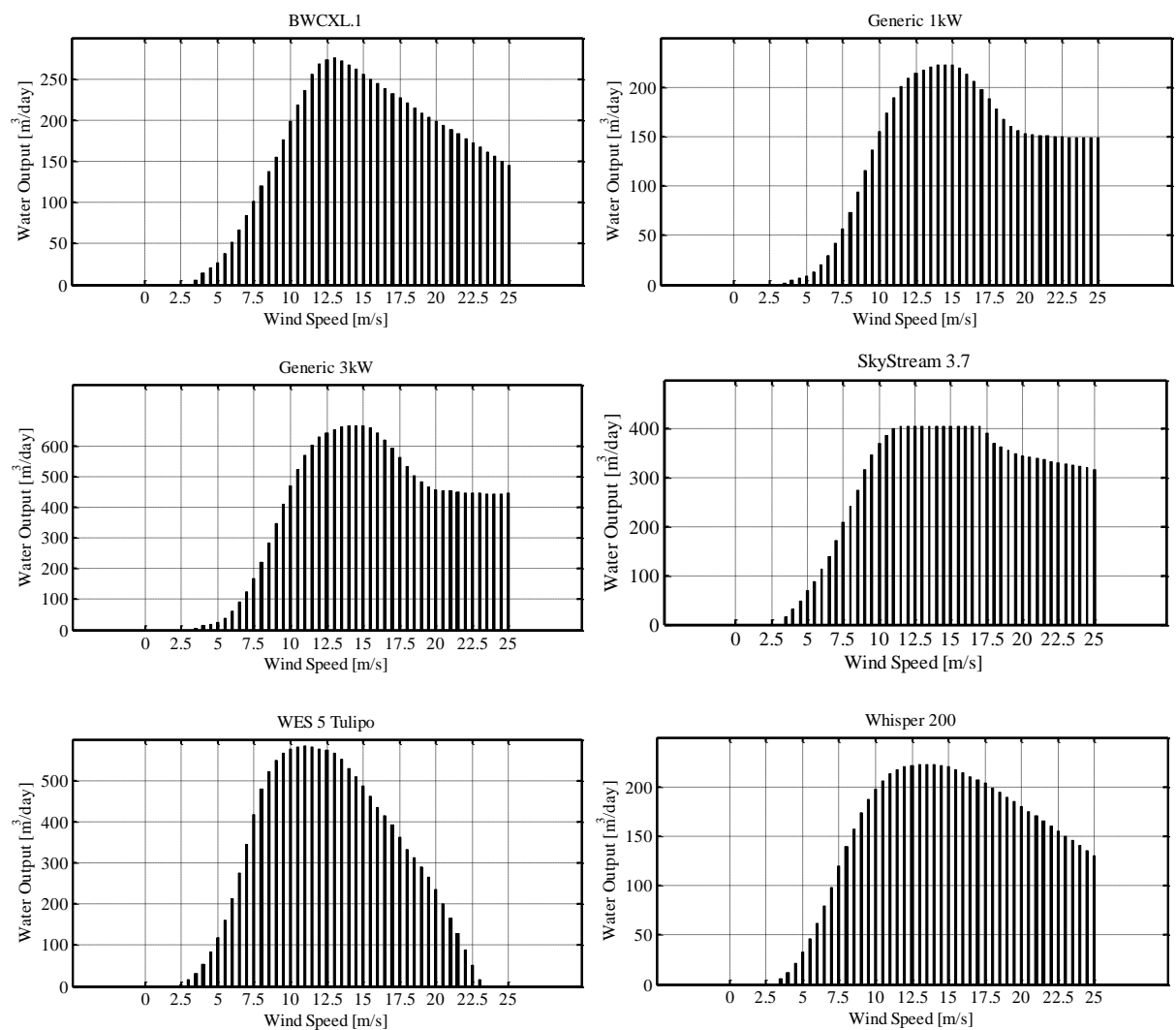
Figure 6.1: Energy Harnessed at Borena using seven different sizes of wind machines.

Consequently, all selected wind turbines are operating under their cut-out speed so that generator power kept from exceeding damaging levels. This show that the motor running the pump is not exposed to higher electricity power. However, due to the fluctuation in the frequency of the electric power the motor may get damaged. Since the VIS Goulds Vertical Submersible Pump is equipped with standard AC induction motor, variation of frequency of

the electric power cannot damage the pump. The pump operates without any difficulty because induction motors can run under variable frequency (0 to 70Hz). Finally, if the problem exceeds beyond the capacity of the system appropriate type of rectifier should be coupled with the wind pumping system.

## 6.2. Performance of Wind Pumping Systems

When the wind pumping systems is working to their full capacity at a specified wind speed throughout the whole year is shown in the figure below. Different wind turbine generators have different wind speed that is required to deliver the required amounts of water to the community.



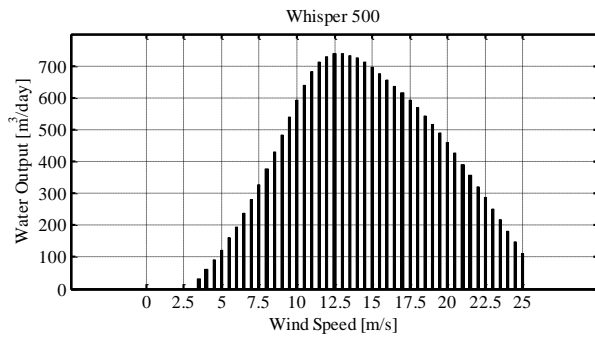


Figure 6.2: Performance of pumping system (candidate WTGs and VIS Goulds Pump).

Referring to the above figures the minimum wind speed required for each candidate wind turbine generator to give the required amounts of water is summarized in table below.

Table 6.1: Minimum wind speed at 25m required to deliver the required amounts of water.

WTGs	BWCXL1	Generic 1kW	Generic 3kW	SkyStream 3.7	WES 5 Tulipo	Whisper 200	Whisper 500
Min. wind speed [m/s]	6.10	7.43	5.83	4.64	4.01	5.76	3.90

The Borena site has average wind speed of 4.8m/s at 25m. Since the higher wind speeds are occurring in the site rarely, the wind turbine generators with minimum wind speed less than the average wind speed of the site would have a better importance than the others. Therefore, *SkyStream 3.7*, *WES 5 Tulipo* and *Whisper 500* are the best choose for the wind water pumping system.

### 6.3. Possible Average Daily Water Output

The figure shown below represents the possible daily water output from the system (WTGs and VIS Goulds Pump) in Borena site. The seven line plots show that how the site wind speed and water output are related while using different WTGs with VIS Goulds Pump.

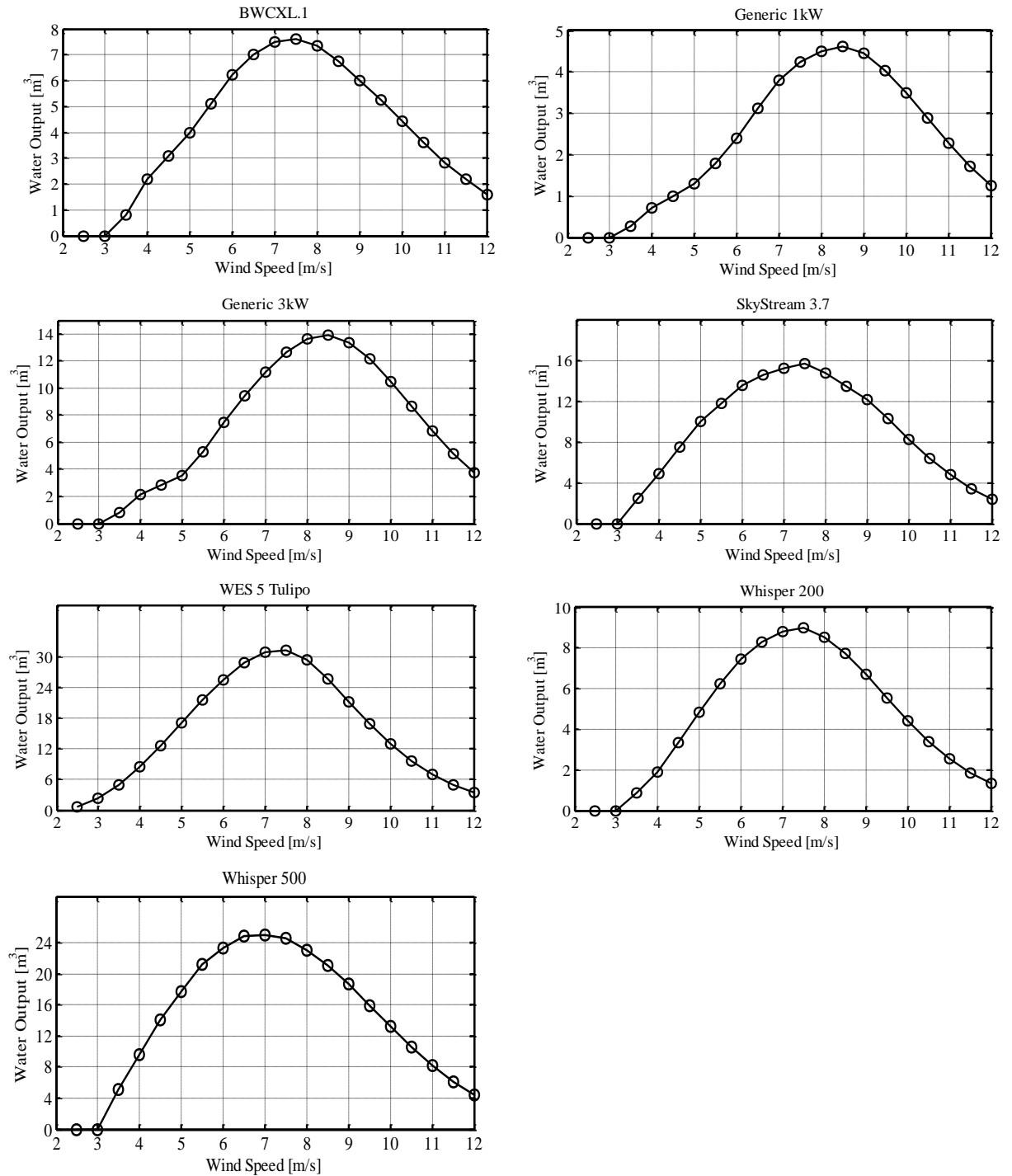


Figure 6.3: Possible average daily water output.

The area under these curves gives the average daily water output from the water pumping system. The larger the area the more water is delivered by the system. Figure 6.4 and Table 6.2 summarizes the above figures.

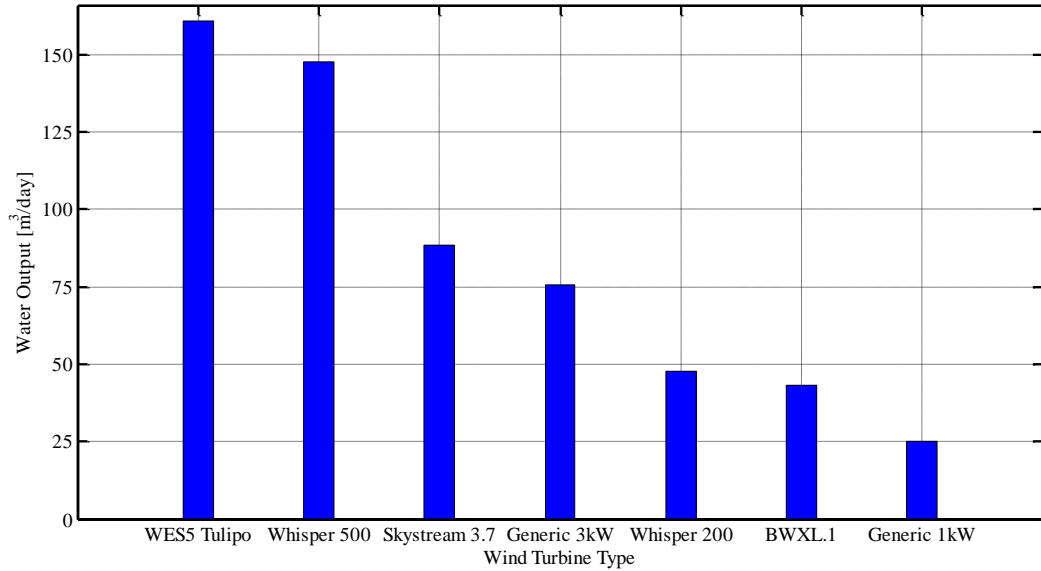


Figure 6.4: Possible water output from each WTGs.

Table 6.2: Average daily water output from each WTGs.

WTGs	BWCXL.1	Generic 1kW	Generic 3kW	SkyStream 3.7	WES 5 Tulipo	Whisper 200	Whisper 500
Daily water output [m³/day]	43.35	25.16	75.46	88.46	160.99	47.67	147.86

According to the above table three of the WTGs are delivering water under the required amounts while the rest are giving more than the daily consumption of the community. Since the daily water consumption in the community is 54.5 cubic meter; *Generic 3kW*, *SkyStream 3.7*, *WES 5 Tulipo* and *Whisper 500* can only satisfy this condition.

#### 6.4. Average Daily Water Output in each Month

From the figure below it can said that *BWCXL.1*, *Generic 1kW*, *Generic 3kW* and *Whisper 200* cannot give the required amounts of water in most months of the year. Hence, using them independently will not satisfy the daily water requirements of the community for most months,

otherwise additional power source is needed. *SkyStream 3.7*, *WES 5 Tulupo* and *Whisper 500* have performed well in satisfying the basic criteria required. They are producing more than the required amounts of water per day in most months.

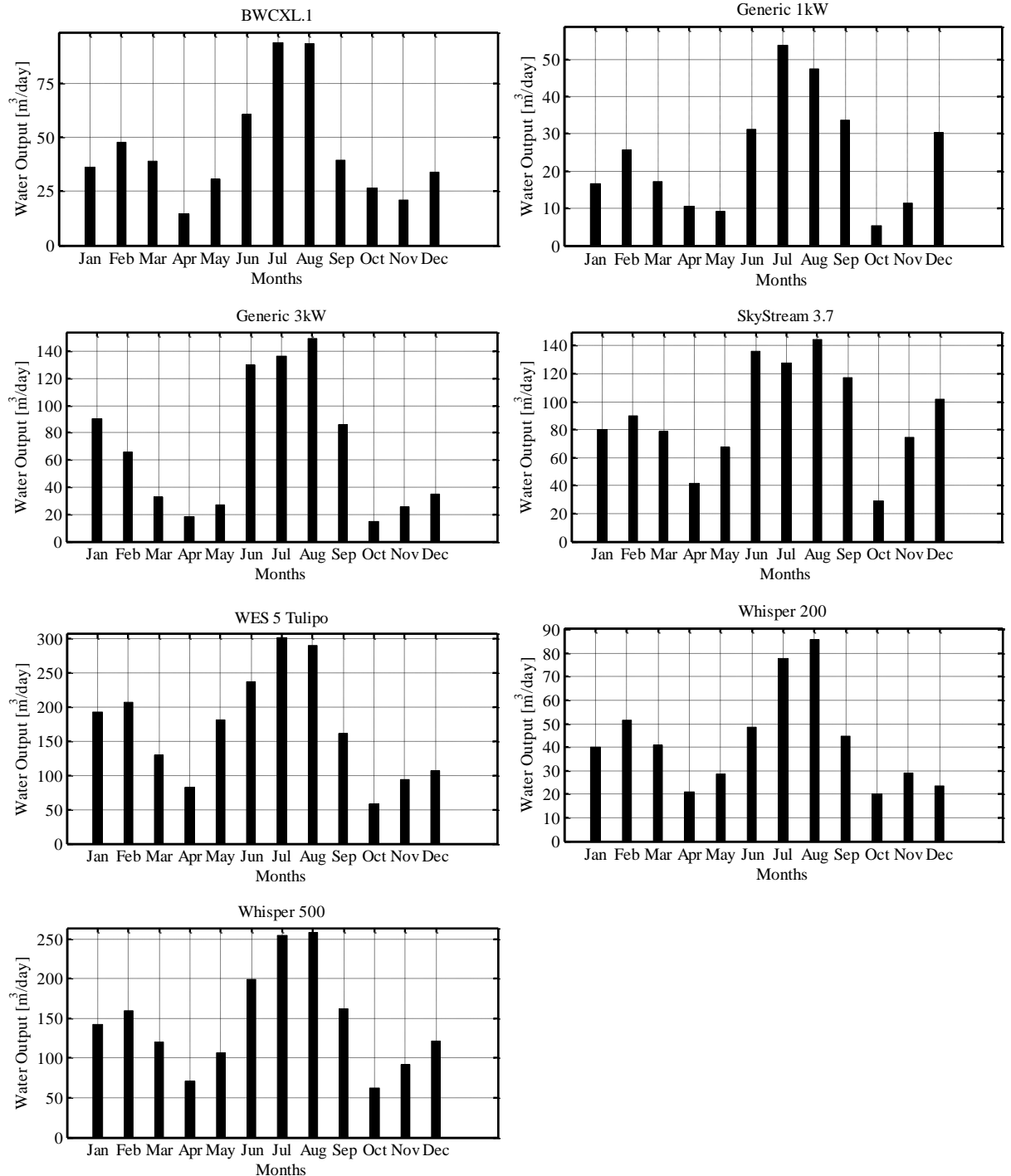


Figure 6.5: Average daily water output over a month.

Referring to the above figures, the wind potential of the site is no longer strong enough from March to May and September to November. As a result, in these seasons the wind pumping systems may not perform well and give the required amounts of daily water. However, in Borena, the average annual rainfall ranges between 350 and 900mm, with considerable spatial and temporal variability in quantities and distribution. Rainfall in the area is bimodal, with 60% occurring in the long rainy season (Gaana), which occurs from March to May, and the short rainy season (Hagaya) from September to November. The long dry season (Biinahagaya) occurs from December to February, and the short dry season (Adolessa) occurs from June to August [5].

Finally, the wind water pumping system is delivering enough amounts of water in the dry seasons and relatively less amounts of water in the rainy seasons of Borena site. In the dry season the water demand giving rise to maximum because natural source of water is not available and hence the societies are only restricted to access underground and surface water. However, the wind water pumping system is delivering enough amounts of water in the dry season, which coincides with the maximum water demand of the society.

To sum up from the technical point of view the three wind turbine generators *SkyStream 3.7*, *WES 5 Tulupo* and *Whisper 500* are feasible. However, from the economical point of which is analyzed in detail in the preceding chapter only *SkyStream 3.7* is economically feasible, which is intended to implement in the allocated site.

## Chapter 7: Conclusion and Recommendation

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### 7.1. Conclusion

The possibility of using wind energy for pumping well water in the Borena site has been studied. Although the Ethiopian Electricity Power Corporation supplies electrical energy to consumers at low prices, extending the service to the remote area of the country may be costly. Therefore, in this project feasibility of constructing a single stand-alone wind turbine for water pumping purposes has been investigated. Wind speed data from the Bale Robe Meteorological Branch Office, Negele Station has been used for the study.

The daily water consumption of the site has been determined by considering both the number of population size using it and water consumption for different needs. The water is mainly used for irrigation of crops and drinking (human and/or livestock) purposes. Therefore, by taking into account these factors the daily water consumption is approximated to be 54.5 cubic meter per day. The depth of static water level was 20m and 4m is considered to be the friction loss.

A vertical industrial pump from Goulds pump has been considered for water pumping purposes that are powered by the wind machines. The pump model VIS is selected using the pump software called ePrism. It is assumed that the pump is operating 4hrs a day to deliver the required amounts of water. Based on this assumption and the amount of water consumption per day, the flow rate is equal to 60gpm. Then, the hydraulic power corresponding to 60gpm and total head of 24m is calculated as 891.08W. Finally, the minimum power required from the WECS is found to be 1470W. In other words, the average annual power to run the water pumping system is 2150kWh.

Seven different sizes of horizontal axis small aero-generators have been considered for the study. They are selected for the analysis based on their application and rated power output. Their rated power ranges from 1 to 3kW and a cut-in wind speed of 2.5 to 3.4m/s.

Based on the statistical analysis of the wind data available in the Borena site, the following conclusions are obtained.

Average monthly variation of wind speed at Borena site is within **3.5** to **6.4**m/s occurred at 25m. The corresponding power density varies between **26.44** to **159.45**W/m<sup>2</sup>. The maximum and minimum of both the monthly average wind speed and monthly average wind power density occurred in August and October respectively. In this site, 63.58% of the wind speed is

above 3m/s. Similarly, the percentage of wind speed exceeding 5m/s is 15.2hr/day on July and August, and 4.6hr/day in October. This helps to assume the minimum operating hours of the system to be 4hrs a day.

The overall wind speed at 25m height is obtained as **4.8** m/s while the average wind power density at the same height was **73.81** W/m<sup>2</sup>. The annual electrical energy generation through wind turbines has been calculated. Its value vary between **991.84** to **6345.91**kWh depending of the size of the wind turbine. The result showed that, only four wind turbines are capable of producing more than the required annual average power. Namely they are: *Generic 3kW*, *SkyStream 3.7*, *WES5 Tulipo* and *Whisper 500*. However, the capacity factor for *Generic 3kW* is about 0.11, which indicates that this wind turbine is not interacting with the regime efficiently. Therefore, the final economic comparison will be carried out for three wind turbines only.

From the analysis carried out, it is found that there is a considerable wind power in the Borena sites for pumping underground water for different purposes. This indicates that this remote area is suitable for harnessing wind energy by using small size wind energy conversion systems.

The net equivalent value of annual wind energy (in terms of USD) generated by various wind machines is estimated according to the Ethiopian Electric Power Corporation tariff. Then, the estimated cost of purchasing and operating such wind energy generating systems have been determined. Economic evaluation of the systems is done by considering life span of the project to be 20 years and 8% real interest rate.

Finally, the net present value of total revenue generated by the wind machines for Borena site have been determined and realized that neither *WES5 Tulipo* nor *Whisper 500* is an economically profitable investment when compared to *SkyStream 3.7*. Finally, the *SkyStream 3.7* has also relatively acceptable internal rate of return and less payback period than the others. Therefore, the *SkyStream 3.7* wind turbine is feasible regarding its performance and profitability for extracting well water in the Borena site.

## **7.2. Recommendation**

- From this research work, it has been found that Borena site has moderately good wind energy potential. Since, the Ethiopian Electric Power Corporation is distributing electrical energy to the consumers at low prices, expanding the service to the remote areas of the country may be costly. Therefore, use of renewable energy like wind is the most promising power source for remote areas in Ethiopia.
- A single wind turbine for extracting well water in Borena has been studied. Therefore, expanding the research to other remote areas and using number of wind turbines will satisfy the power requirement and change the life style of the societies in these sites. In other words, enables the pastoralists to settle in their woredas and kebeles, and avoid seasonal migration and unnecessary conflict between different clans and ethnic groups.
- However, the initial investments is relatively larger the country (government, non-governmental organizations and the public) should accept this technology that brings multilateral (social and economic) developments.

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## Appendix A: Wind Speed and Electricity Energy Sales Price

### A.1. Wind Speed Data

Borena daily wind speed measured at 2m above the ground surface. To get the wind speed in m/s, each value in the table must be multiplied with a factor of  $100/(24 \times 3600)$ . [Source: Bale Robe Meteorological Branch Office, Negele Station]

2004(WR)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
1	2299	2166	2419	2228	2739	2444	2147	2523	2738	2661	2438	2096	1658	1381	2242	2035	1928	1837	1555	2016	2068	1777	2178	1064	1430	2485	2404	2099	1637	2078	2571
2	2002	1109	1275	1511	1743	2648	2821	2810	3367	2942	2841	2965	2173	1999	1774	1591	1337	1906	2097	2669	2311	2380	2902	2831	3042	2295	2350	2345	2622		
3	3046	3134	2555	2608	2162	2334	2772	2221	2120	1989	2279	1662	2216	2034	1699	1782	1648	2003	2463	2253	2279	2564	2754	2300	1999	2042	1470	1848	2155	1515	1566
4	2091	1682	1653	1326	1472	1143	1361	1442	1839	1310	1412	1908	1426	1094	1760	1890	1608	1554	1978	1902	1183	1511	1664	1378	1537	1711	1333	1472	2242	2534	
5	1919	1944	2087	2108	2117	1942	1860	1749	1909	1980	2007	2146	2418	1943	1593	1521	1863	1523	1109	2135	2103	2495	2339	1806	1907	2185	2016	2480	2099	2032	1864
6	1775	2085	1896	2656	2351	2047	2900	3357	2452	2523	2674	2137	2611	2602	2837	2498	2302	2940	2483	2251	1821	3083	2915	2554	2700	2597	2600	3125	3128	2631	
7	2800	3301	2746	2315	3249	2644	3091	2734	2272	3301	3180	2740	2521	2691	2972	2630	3095	3347	3954	3156	2994	3032	3022	3581	2784	3034	3417	4249	4760	3656	3591
8	3461	4180	3751	3405	3047	4065	3808	3432	3209	2672	2752	2641	2735	2931	3373	3015	2931	3497	3300	3547	2778	3343	2675	2809	2964	3000	2688	2701	2219	2850	2265
9	2323	2027	1914	2046	1944	2142	2151	2384	2890	3256	2432	3017	3487	2314	2091	2352	2396	2041	1811	1845	1714	2083	2240	1858	2004	1887	1662	2081	2288	2221	
10	2429	2135	2492	1729	2717	1959	1849	1836	2138	1741	1761	1218	1340	1801	1818	2120	2046	1633	2193	1626	2097	2117	2200	2286	1663	1803	2402	1501	2014	1298	1325
11	1369	1273	972	1079	1857	1755	1933	1252	1551	1241	1900	2651	2508	2118	1139	1619	1947	1386	1236	1259	1639	1357	1678	1950	2158	2308	1991	2696	2429	2013	
12	1384	1724	2288	2125	2327	2395	2294	2344	1635	1748	2652	2438	2120	1930	1617	1777	1969	2496	2277	1983	1204	1526	1853	1896	2892	2398	1757	1948	2195	2547	2516
2005(WR)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
1	2667	2690	1934	1867	1667	1634	1801	2146	2621	2000	2046	2253	2389	2055	1848	2119	2020	1964	1754	2441	3007	2008	1752	1851	1613	1613	1782	1480	1554	1505	2580
2	3112	2349	1549	1760	2006	2062	1975	1993	2029	2526	2809	2107	2073	1640	2796	2600	3140	2899	2791	2896	2983	2546	2148	2048	1962	1839	1595	1744			
3	1785	1878	1890	1247	1969	1719	1916	2472	2145	1762	2054	1774	1670	1751	1942	1718	1450	1559	1776	1609	1824	1603	1705	2049	2701	2912	2793	2377	2851	2991	3199
4	2964	1972	1553	1673	1658	2017	1570	1886	1899	2148	2133	2009	1640	1419	2267	1794	1517	1738	1692	1423	2193	1476	1194	1312	1917	2161	2583	1364	1834	2113	
5	1281	2355	2309	2265	2158	1050	2077	1987	1683	1744	2046	2927	1630	2299	1545	1417	1556	1246	1218	1217	1954	1368	1877	1683	1367	1421	1313	1595	1138	1950	1870
6	1901	1955	1826	2411	2371	2309	2098	1625	1746	2520	2381	2618	2293	2174	2550	2537	2714	2713	2482	2727	2563	2539	2573	2214	2707	2635	2296	2923	2872	2764	
7	2736	2679	2509	2503	2788	2731	2582	3267	3759	3777	3423	4043	2647	2964	3534	2943	2129	3358	2842	2262	2345	2609	2997	2662	2914	2452	3081	2929	2509	2985	3314
8	2841	3088	2766	3055	2529	2253	3155	2393	3006	2380	2353	2451	2312	2017	2704	3311	2937	2523	2833	2691	2763	3036	2944	2341	2565	2815	2454	2512	2420	3382	3149
9	2764	2310	2801	3020	3068	2336	2410	3093	2390	3866	3456	3420	2727	3257	3467	3057	2624	2208	2257	2044	1994	2083	2687	2441	2065	1813	1705	2003	1608	1681	
10	1910	1408	1411	1668	1530	1420	1710	1806	1915	1678	1338	1062	1663	1192	1488	1899	1604	1305	1367	1124	1333	1728	1331	1561	1788	1642	1724	1396	1680	1593	1427
11	1002	1684	1347	1265	1624	1444	1699	1640	1357	1611	1656	1739	2120	2202	1721	1302	1157	1046	2197	1392	1525	2294	2753	2700	2576	2510	2360	2068	1849	1883	
12	1828	2057	1991	1930	1972	2292	2554	2701	2434	2689	2689	2520	2995	2289	1980	2132	1997	2561	2024	2509	2627	2466	2286	2109	1834	2344	2975	3271	3087	2689	2783

2006(WR)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
1	2794	2401	2339	2573	2677	2635	1944	1886	1919	1980	2210	2584	2264	1430	1711	2100	2456	2297	2490	3231	3225	3096	3528	2786	2899	2614	2078	1917	1982	1985	2429
2	2413	3082	2862	3100	3098	2317	2500	2467	2307	2227	1779	1855	2127	2057	2789	2695	1690	1894	1797	1925	1958	2025	1563	2031	1802	1546	1779	2106			
3	1711	1728	2434	1780	2008	1823	1982	2286	2370	1598	1755	1433	1454	1773	1630	1592	2031	1440	1670	1936	1616	1442	1440	1742	2204	2307	2104	2705	1224	1916	1490
4	1621	1068	1170	1536	2468	1473	1145	1575	2304	1948	2002	1834	1865	1778	1411	1418	1532	1576	2288	1321	1421	1337	1267	1414	1842	2161	1898	1421	1702	1467	
5	1847	1340	1820	1328	1466	1703	1498	1336	1202	1361	1194	1345	1354	1284	1498	1627	1632	1201	1449	1478	1274	2017	2124	2188	1956	1899	2000	2538	2828	2816	2829
6	2353	2655	2655	2838	2781	2305	2475	2309	2628	2026	1950	2741	2341	2214	2226	1959	1988	2908	2880	3452	3067	3562	3500	3140	3395	3151	3043	3019	2587	2829	
7	2694	2625	2772	2380	2841	1928	2485	2382	2649	3285	3043	2893	2698	2972	2234	3350	2814	2891	2634	2759	2972	2625	2866	2161	2670	2253	3202	3713	2853	2463	2872
8	2460	2002	2573	2602	3268	3226	3535	3330	2957	3013	2753	2602	2296	3067	3439	2243	3200	2553	2765	3137	3424	2837	2704	2819	2181	2771	1825	2974	2839	2282	2571
9	3294	2770	2002	3290	3478	2774	3448	3013	2513	3061	2836	2720	2322	2463	2208	2619	1522	2049	1785	2412	1890	2434	2814	2175	1907	2024	1771	1740	2012	2039	
10	1462	1187	1436	1616	1455	1224	1448	1455	1782	1537	1786	1165	1565	1413	1266	1609	1302	1143	1389	1237	1711	1930	1689	1249	1924	1725	1638	1805	1334	1395	2105
11	2162	1971	2106	1888	1719	1992	1906	1643	1745	1854	1917	2054	1968	1437	1680	1677	1366	1660	1361	1301	1398	1599	1510	1908	1676	1328	1043	1643	2051	2084	
12	1952	1996	1363	2075	2125	2348	1672	1828	2696	2106	1828	1949	2105	2136	2148	1930	1691	2176	2002	1862	1491	1496	1468	1455	1607	2094	1765	1178	1764	1796	1984
2007(WR)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
1	2519	2552	3389	2631	2522	2264	1706	1719	2032	2230	2168	1915	1942	2302	1572	1630	1986	2778	2559	2513	2239	2278	1737	1544	2454	2304	2116	1978	1581	1528	1437
2	2081	1701	2019	1915	2262	2348	2821	2241	2047	1880	1865	2400	1984	1368	2406	2301	2425	2500	2493	2807	2787	2856	1738	2149	2275	1926	2034	2275			
3	2406	2691	3021	2872	3026	2926	2966	2096	1563	2155	1935	2435	2234	2166	1897	1859	1889	1416	2238	1351	2306	2370	2077	2087	2343	1934	1672	1895	1426	1787	1861
4	2548	2447	1501	1762	1904	1820	2470	2152	1732	1374	1790	2213	1751	1720	1184	1248	1327	1373	1285	1597	1452	1899	1563	1883	1388	1340	1494	1229	1380	1308	
5	1511	1154	1598	1241	1256	1548	2520	2364	2358	1857	2956	1920	2108	2468	2263	2220	2204	1303	2034	1466	1440	1711	2172	2062	2214	2080	3121	2403	2276	1754	1894
6	1555	2500	1440	2600	2488	3223	1975	2089	2082	2402	2942	2584	2780	2787	2863	3473	3118	3110	3517	3315	3588	3195	3975	3531	2713	2496	1191	2466	2182	2392	
7	2929	3258	2723	2532	1970	2337	2263	2427	2448	2135	2517	2123	2801	2906	2324	2973	2986	2418	2696	2745	2876	2959	2314	2643	2978	3229	2717	2167	2362	3913	2564
8	2837	3367	2921	3033	3137	2924	2856	2273	2722	3127	2759	2669	2581	2773	2153	1911	2229	2498	2690	3375	3060	3725	2301	2106	2492	3762	2658	2961	2757	2679	2786
9	3323	3240	2912	2942	2695	2918	3061	3201	2624	2222	2163	3199	2539	2323	2338	1769	2401	3131	2735	2244	2427	2858	2027	2337	2447	2507	1740	1734	2975	1721	
10	2172	1853	1142	1071	1188	1515	1415	1292	1293	1195	1723	1793	1260	1808	1808	1704	1704	1193	1088	1506	1266	1718	1932	1925	1963	1776	1466	894	1144	1455	1211
11	1262	1104	1150	1446	1723	2405	2419	2306	2218	2554	2976	2436	1119	220	2142	2201	2407	2241	2324	2213	2374	2116	2284	2180	2280	2277	2465	2540	2485	2130	
12	2158	2220	2217	2406	2474	2383	1660	1892	2096	2168	2360	2444	2148	2097	2549	2847	3103	2665	1653	1531	1752	2090	2538	1990	3113	3177	3026	3010	2030	2501	2525

<b>2008(WR)</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>	<b>7</b>	<b>8</b>	<b>9</b>	<b>10</b>	<b>11</b>	<b>12</b>	<b>13</b>	<b>14</b>	<b>15</b>	<b>16</b>	<b>17</b>	<b>18</b>	<b>19</b>	<b>20</b>	<b>21</b>	<b>22</b>	<b>23</b>	<b>24</b>	<b>25</b>	<b>26</b>	<b>27</b>	<b>28</b>	<b>29</b>	<b>30</b>	<b>31</b>
<b>1</b>	2552	2226	2287	2317	2341	2474	1992	2172	2246	2605	2007	2260	2257	375	2644	3049	3200	3759	2888	2663	2409	1732	2243	2435	2762	2756	2256	2390	3058	2266	2402
<b>2</b>	287	2862	2643	1813	1966	1774	1814	2213	3150	3759	2955	2328	1760	1670	2346	2958	2866	2901	3159	2525	3395	3450	2826	2695	2285	1831	2149	2589	2594		
<b>3</b>	2517	2087	1921	1705	1922	2966	2272	3392	2836	2310	2061	1741	1901	1631	1920	2367	1980	1588	1116	1980	2178	2352	2119	1730	2013	2020	1795	1987	1586	1854	1650
<b>4</b>	1469	1628	1602	1938	1990	2040	1842	1448	2273	1078	1860	1427	1631	1797	1347	1672	1275	1237	1632	1773	2067	1957	1485	1672	2196	2156	1505	1522	2331	2547	
<b>5</b>	2024	2020	2125	1540	1770	2150	2052	1806	2598	2043	1436	1800	1324	1925	2640	2108	2692	2508	3165	2690	1992	2232	3164	2667	2408	2442	2220	3321	3558	3558	2332
<b>6</b>	2856	2864	1931	1907	2062	1502	2534	3057	2486	2847	2351	1744	2745	2196	3307	3047	3801	3241	3548	2629	3085	2500	2756	2592	2258	2687	2610	2425	3241	3699	
<b>7</b>	3129	2910	3317	2395	3065	2889	2605	3675	2956	3580	3168	2951	3190	3480	2944	3614	3166	4093	3397	3940	2529	2646	3493	3136	3065	3599	3222	3220	3470	2496	2573
<b>8</b>	2814	3026	3087	3513	3787	3282	3621	3201	4447	2750	4472	2725	2358	2785	3117	3128	2709	3088	3232	2627	2499	3033	2979	3987	3036	2642	2652	2120	2634	2893	2382
<b>9</b>	2937	2824	3747	2801	2532	3253	2869	3300	2782	2601	2539	3456	2972	2572	2024	2213	2063	1366	1606	1325	1657	2259	1811	1298	1426	1618	1870	1540	1795	1698	
<b>10</b>	1209	1322	1687	1521	1530	1530	1504	1591	1397	1433	1239	2009	1478	1462	1355	1527	1405	1662	1700	1554	1970	2578	1405	1662	1549	1848	1351	1318	1528	1049	1455
<b>11</b>	1852	1302	1765	1756	1372	1375	1527	2223	2413	2204	1933	1722	1632	1579	1782	2050	2040	2065	2165	2022	2024	1409	1889	1990	1441	1481	1360	1637	2115	1942	
<b>12</b>	1591	1246	1367	2212	1905	1829	1778	1842	1705	2085	1805	1762	1990	1449	1525	1606	1986	2283	2371	1420	2102	2023	1863	1731	2303	2166	2254	1840	2080	2765	2377
<b>2009(WR)</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>	<b>7</b>	<b>8</b>	<b>9</b>	<b>10</b>	<b>11</b>	<b>12</b>	<b>13</b>	<b>14</b>	<b>15</b>	<b>16</b>	<b>17</b>	<b>18</b>	<b>19</b>	<b>20</b>	<b>21</b>	<b>22</b>	<b>23</b>	<b>24</b>	<b>25</b>	<b>26</b>	<b>27</b>	<b>28</b>	<b>29</b>	<b>30</b>	<b>31</b>
<b>1</b>	2660	2220	2585	2305	1882	2140	2025	2319	2149	2053	1848	2611	2595	2691	2712	2362	2282	2013	1849	1703	2313	2661	1231	1799	1302	1993	1424	1726	1544	1976	1647
<b>2</b>	2548	2736	2043	2575	2682	2995	1357	2629	3213	2699	2165	2105	1998	1932	1859	1730	2210	2174	2667	2317	1979	1709	1800	2600	2665	2395	2179	2384			
<b>3</b>	2243	2153	2491	2648	2779	2402	2598	2224	1925	1760	1623	2178	2349	2389	1916	2057	1921	2454	2447	2558	2149	1791	1788	2079	2271	1697	1967	1221	1917	1377	2099
<b>4</b>	1335	1596	2001	1759	1896	2378	1995	1994	1701	1586	1525	1462	1177	1731	1701	1936	1801	1644	1544	1295	1813	1873	1686	1466	1702	2088	1718	1635	1548	1831	
<b>5</b>	1035	2562	1965	1341	2210	2572	1880	1179	1392	1737	2157	1233	2729	1570	1825	1466	1738	1718	2386	1834	1995	2132	2124	2030	2113	1926	2187	2328	1475	1282	1156
<b>6</b>	1575	1620	1723	1546	2359	2258	2777	2267	2252	2001	2007	2020	2775	3108	2373	2406	2328	2302	1815	1356	1969	1829	2337	1961	2624	1976	2760	2908	2728	2984	
<b>7</b>	2934	2549	2060	2674	2950	3808	2191	3172	2437	2506	2578	2776	3179	3056	3451	3182	3414	2930	2444	3040	2963	1808	2260	1892	3135	3043	2844	2463	2804	2392	3046
<b>8</b>	1711	2362	2616	2516	3394	3425	3090	3290	3030	3603	3361	2561	2551	3109	3113	3185	2948	2400	2278	3125	2876	3192	3360	3022	3437	2695	2535	2592	3090	3324	2317
<b>9</b>	2399	2740	3063	3429	3294	3635	3245	2739	2914	2653	1842	2293	2803	2952	2068	2036	1700	1682	1303	1730	1649	1627	1670	1997	1630	1629	1463	1488	1548	1854	
<b>10</b>	1452	1484	1735	1535	1858	1742	1752	1544	1334	1671	1699	1291	2006	1404	1789	2046	2138	1823	1790	1967	1607	1526	1058	1569	1416	1335	1260	1307	2063	2189	2106
<b>11</b>	1803	1609	1927	2420	2370	2280	2282	2197	2048	1824	1415	1364	1282	1535	1694	1641	1552	2367	1704	1926	1808	1660	1479	2428	2268	2107	2013	1574	1541	1901	
<b>12</b>	2550	2392	2032	1816	1646	1818	1618	1430	1633	1510	1253	1726	1352	1621	1903	2632	2086	2096	2501	2725	1760	1486	1623	1868	1804	1874	1097	1288	1441	940	1001

## A.2. Electricity Energy Sales Price

Ethiopian Electric Power Corporation Existing and Proposed Electricity Energy Sales Price Comparison

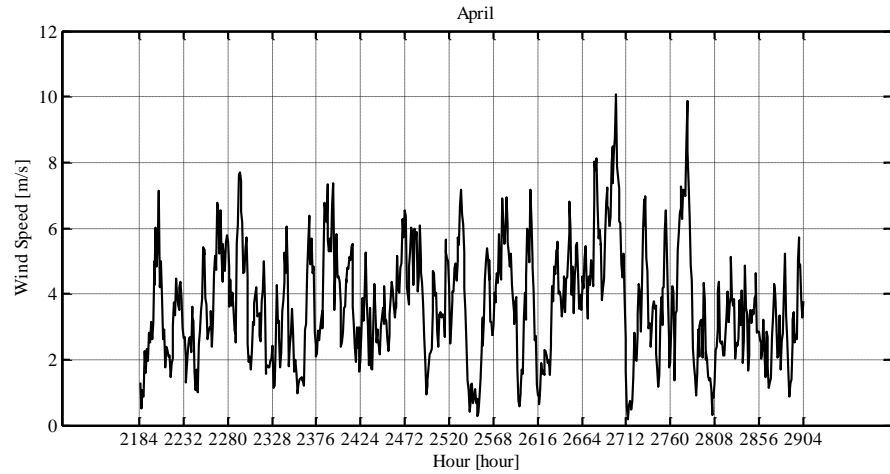
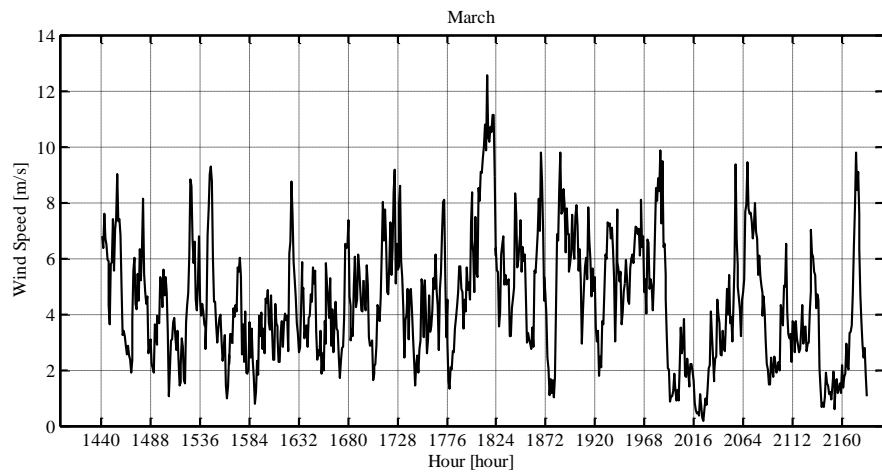
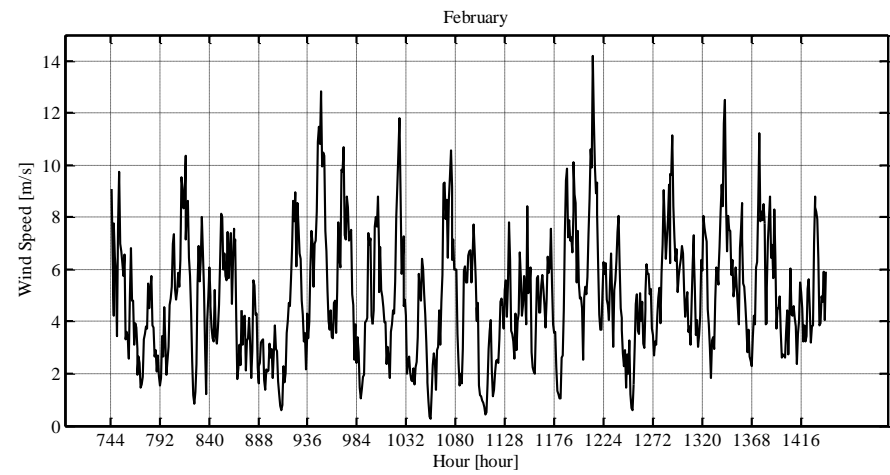
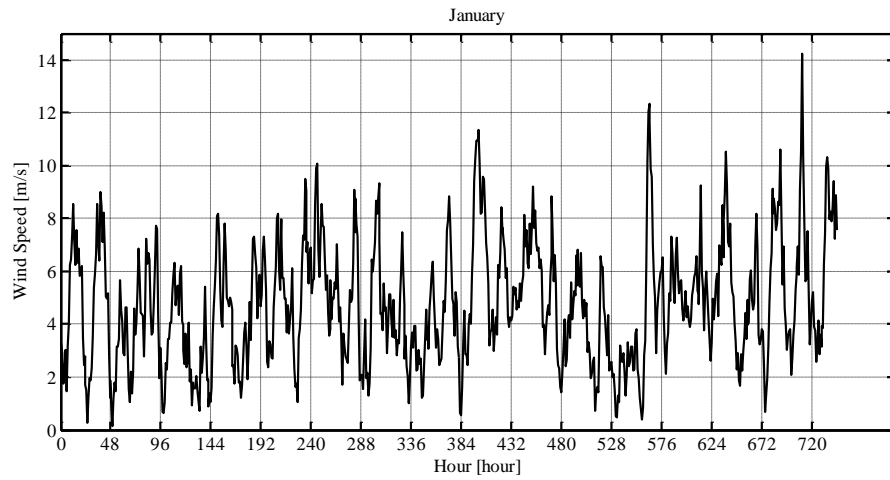
Table A.1: Electricity Energy Sales Price (Tariff). [Source: EEPCO, Sebeta Branch]

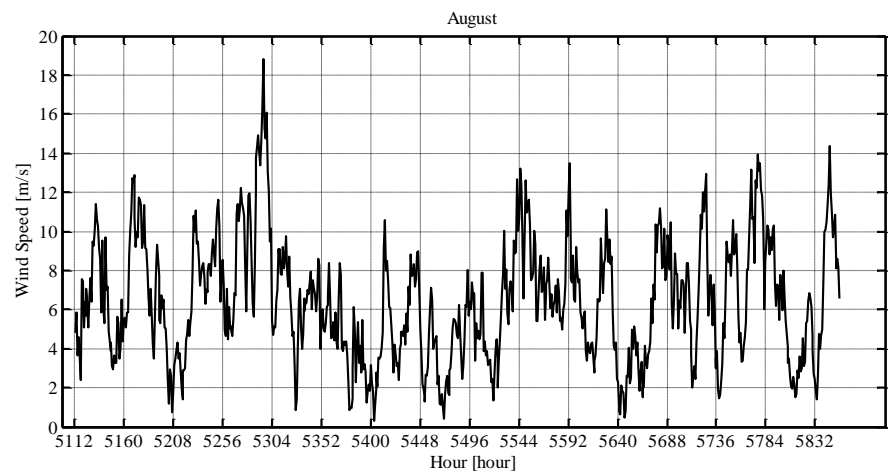
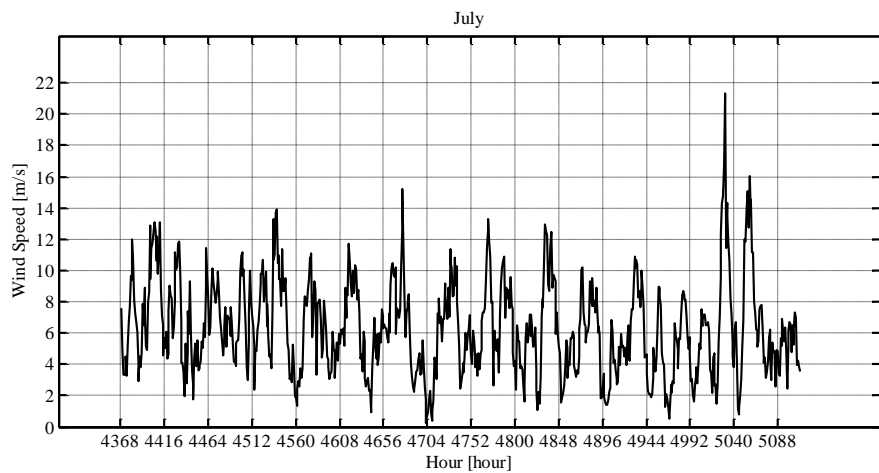
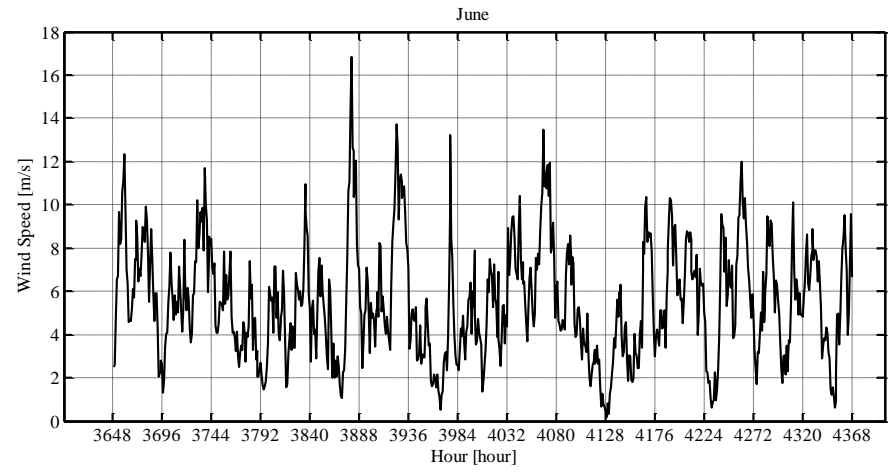
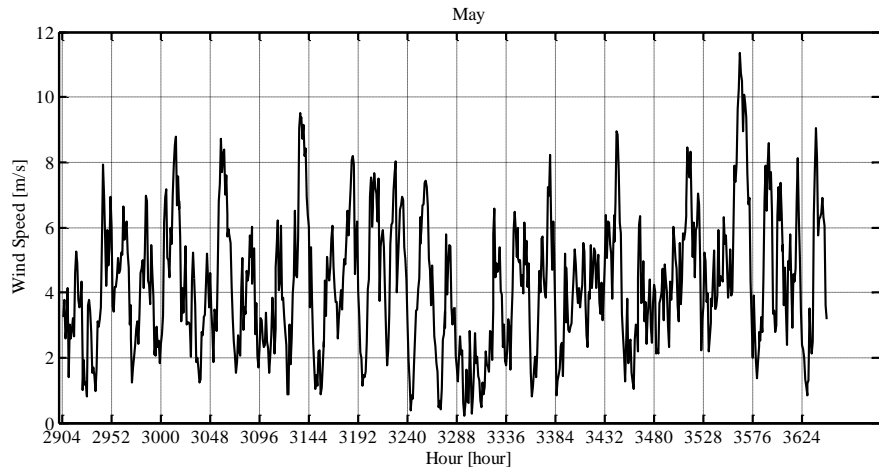
Tariff Category and Block ID	Monthly Consumption kWh	Existing Elec. S. P. (Tariff Rate)	Elec. S. P. (Ta. Rate) Changes	PROPOSED Elec. S. Price (Tariff Rate)
Domestic				
Equivalent Flat Rate		0.3897	0.0838	0.4735
1 <sup>st</sup> Block	0-50	0.2730	0	0.2730
2 <sup>nd</sup> Block	51-100	0.2921	0.0643	0.3564
3 <sup>rd</sup> Block	101-200	0.4093	0.0900	0.4993
4 <sup>th</sup> Block	201-300	0.4508	0.0992	0.5500
5 <sup>th</sup> Block	301-400	0.4644	0.1022	0.5666
6 <sup>th</sup> Block	401-500	0.4820	0.1060	0.5880
7 <sup>th</sup> Block	Above 500	0.5691	0.1252	0.6943

If a system is producing/utilizing 285kWh a month, then it belongs to in the 4<sup>th</sup> Block. The amount of birr equivalent of the produced/utilized electricity can be calculated as follows:

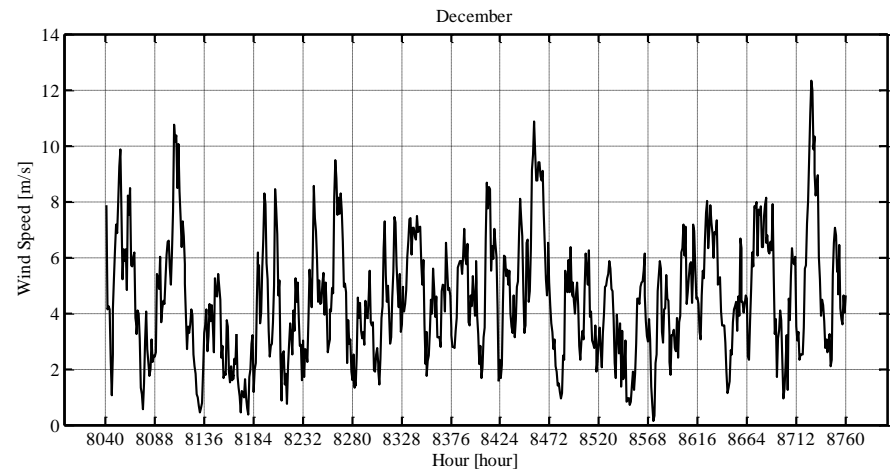
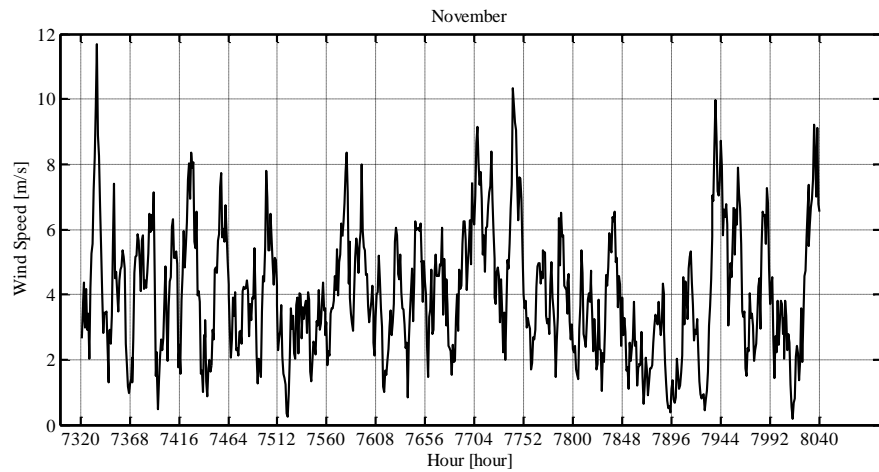
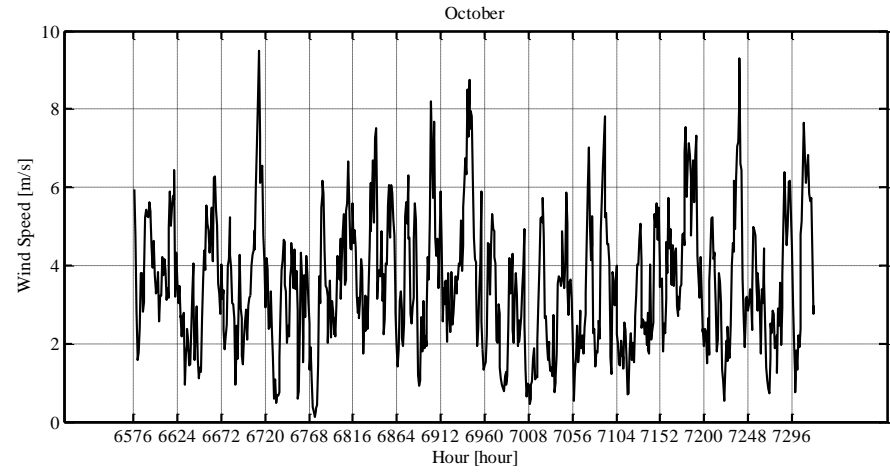
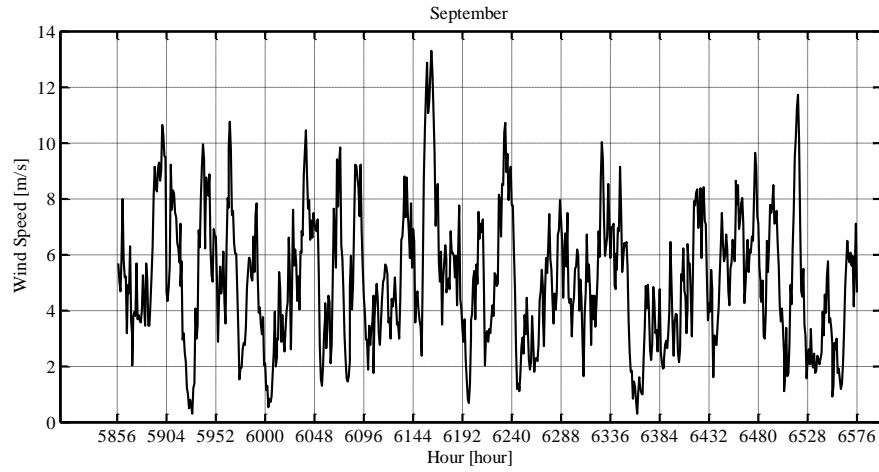
$$\text{Total Tariff} = 50 \times 0.2730 + (100 - 50)0.3564 + (200 - 100)0.4993 + (285 - 200)0.55 = 128.15 \text{ ETB/month}$$

## Appendix B: Average Hourly Wind Speed for Each Months at 25m





Feasibility Study of Use of a Horizontal Axis Aero-generator for Well Water Lifting in Borena, 2013



## Appendix C: Goulds Pump Selection

To find the efficiency of the Goulds VIS Vertical Industrial Submersible Pump, the software Pump Selection System (PSS) was used. **NOTE:** access was granted after installation and registration.

In the Basic Criteria the flow rate was set to 13.62 m<sup>3</sup>/hr and the total dynamic head to height of 24m.

The screenshot shows the ePrism software interface for pump selection. The window title is "ePrism - US Item # ITEM 001". The menu bar includes "File", "Actions", "Settings", and "Help". A toolbar on the right has an "Items" icon. The main area is divided into three tabs: "Criteria", "Results", and "PumpSmart Calculator".

**Criteria Tab:**

- Basic Criteria:** \*Flow: 13.62 m<sup>3</sup>/hr, \*Total Dynamic Head: 24.00 m, Cycles: 60Hz. Buttons: "Run Slurry Correction Process".
- Liquid Properties and Operating Conditions:** Name: Water, Item No: ITEM 001, Sp.Gr.: 1.000, NPSHa: [blank] m, Viscosity: 1.000 cp, Temp(R): 21.1 deg C, Vapor press.: [blank] bar abs. Service: [blank]. Radio buttons:  Lethal or Toxic,  Non Hazardous.
- Optional Selection Criteria:** % Headrise to Shut Off min: [blank] to max: [blank], Nss less than: [blank] m<sup>3</sup>/hr,m,  Allow Near miss selections. Operating Point to be % BEP min: [blank] to max: [blank], Impeller diam: No constraint. Max NPSHr Margin %: [blank], Max. Allowable Shut Off Pressure: [blank] bar g.

**Selection List:**

*Speed:	*Models
<input checked="" type="checkbox"/> 3600	<input checked="" type="checkbox"/> V3298 Overhung Impeller, Vertical In-line, ANSI, Seal-less, Te
<input type="checkbox"/> 1800	<input type="checkbox"/> VHS Vertical Cantilever Vortex Pump, Recessed Impeller
<input type="checkbox"/> 1200	<input type="checkbox"/> VIC Double-casing diffuser vertically suspended pumps
<input type="checkbox"/> 900	<input checked="" type="checkbox"/> VIS Vertically suspended, single-casing diffuser pumps wi
<input type="checkbox"/> 720	<input type="checkbox"/> VIT Wet pit, vertically suspended, single-casing diffuser pu
<input type="checkbox"/> 600	<input type="checkbox"/> VJC Vertical Cantilever Slurry Pump
<input type="checkbox"/> 515	<input type="checkbox"/> VRS Vertical Cantilever Rubber-Lined Slurry Pump, Open In
<input type="checkbox"/> 450	<input type="checkbox"/> XHD Extra Heavy Duty Metal Lined Slurry Pump

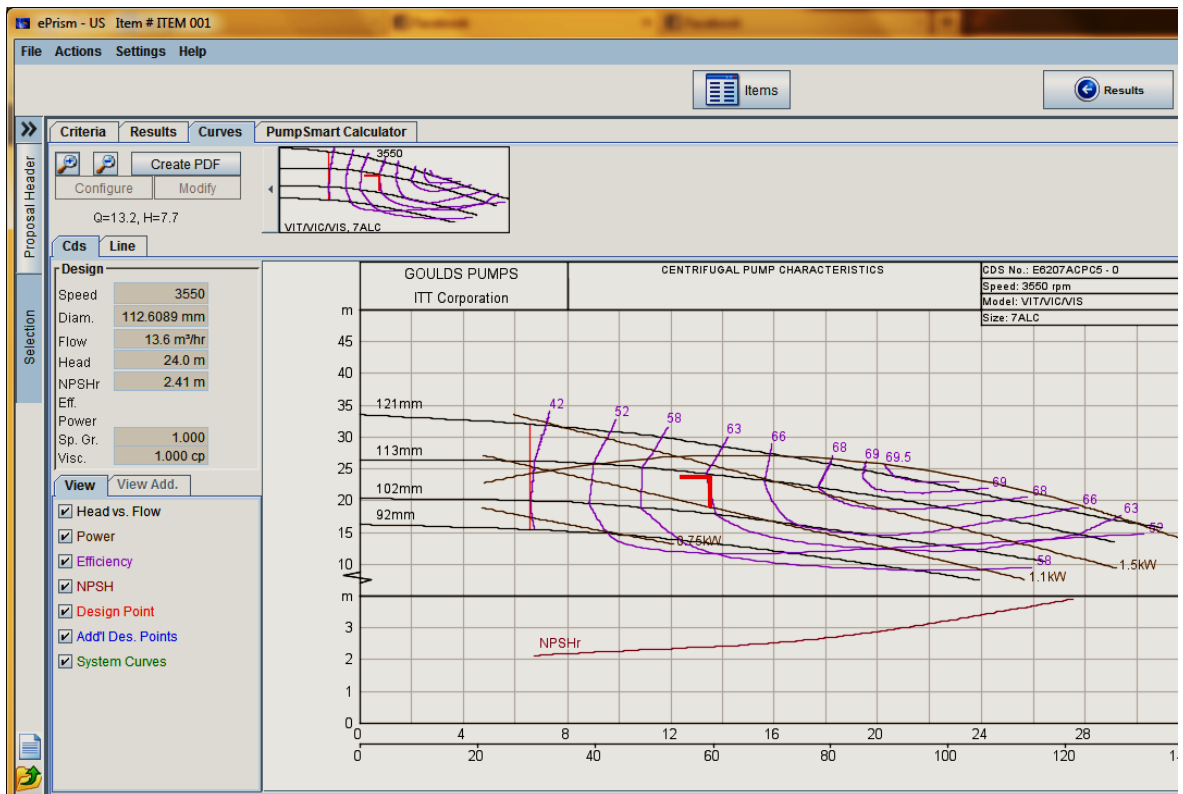
Buttons: "Search by Model and Size", "Search Using Selection Criteria", "More Info".

Bottom tabs: "Criteria", "Advanced", "Slurry Correction".

When pressed the icon "Search Using Selection Criteria", the ePrism software searched for a pump which matched the criteria. Seven pumps with different parameters were found. For further analysis the one with highest efficiency was selected, Goulds VIS 7ALC.

Criteria	Results	Curves	PumpSmart Calculator						
Criteria Match for Q = 13.62 m <sup>3</sup> /hr, H = 24.0 m 4 Pump Sizes Found									
Model	Type	Group	Size	Stg No	RPM	Feature	%BEP	Power	Eff
<input checked="" type="checkbox"/> VIT/VIC/MIS	Vertical Turbine		7ALC	1	3550		68.00	1.47	60.6
<input type="checkbox"/> VIT/VIC/MIS	Vertical Turbine		6ALC	2	3550		124.00	1.47	60.2
<input type="checkbox"/> VIT/VIC/MIS	Vertical Turbine		7AHC	1	3550		61.00	1.50	59.1
<input type="checkbox"/> VIT/VIC/MIS	Vertical Turbine		6CLC	1	3550		35.00	2.14	41.4

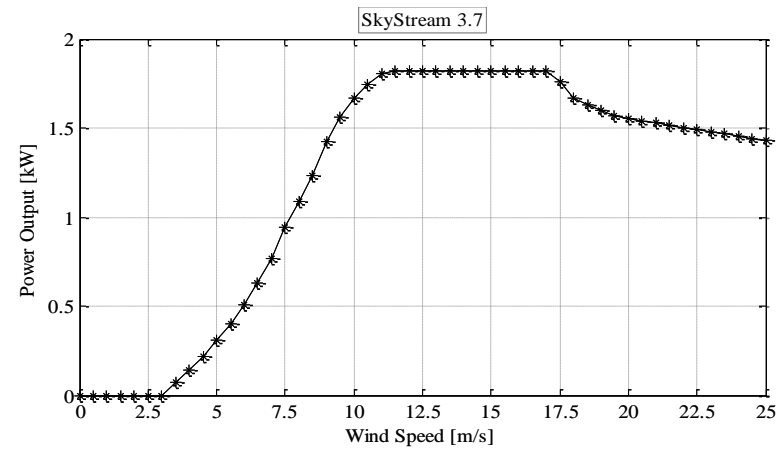
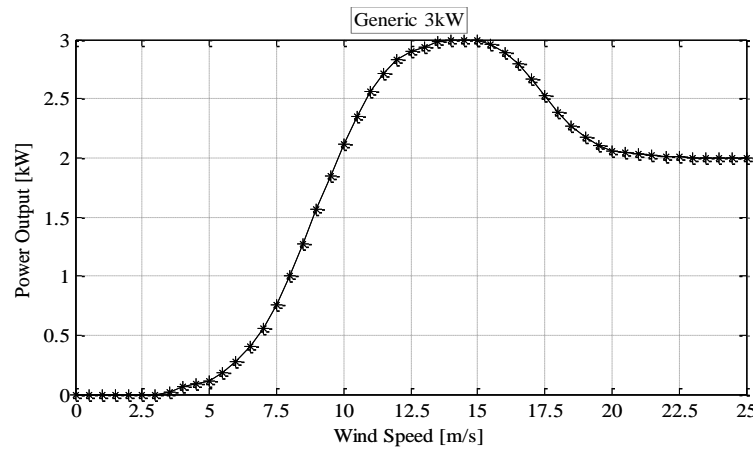
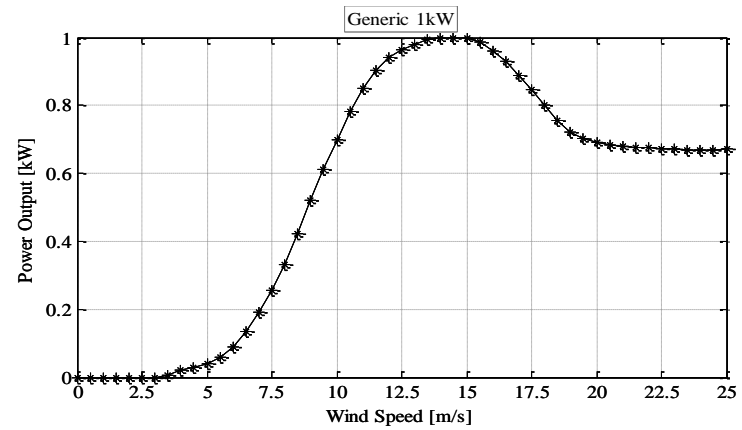
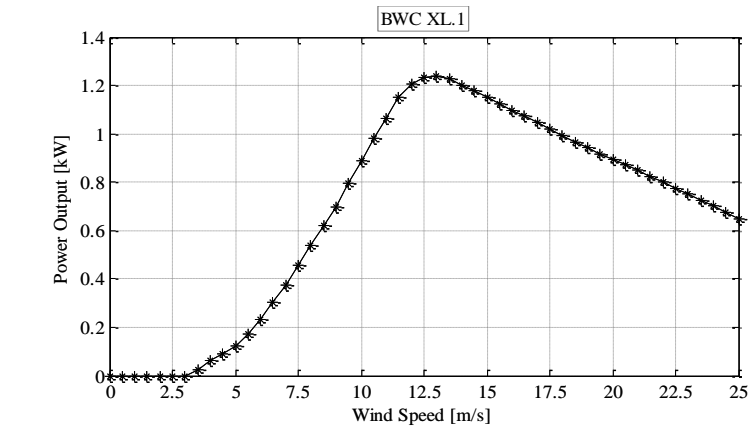
The Goulds pump of type Vertical Turbine, size 7ALC and speed of 3550RPM has efficiency of 60.6%. The pump uses 1.4665kW when pumping up to a height of 24m, at a flow rate of 13.62 m<sup>3</sup>/hr.

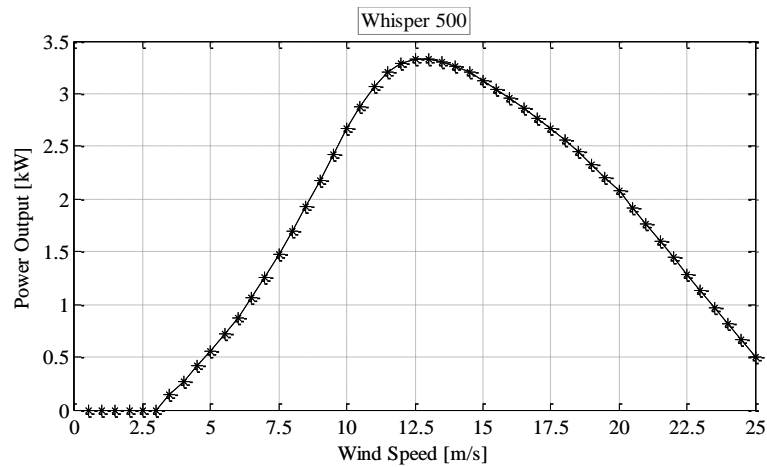
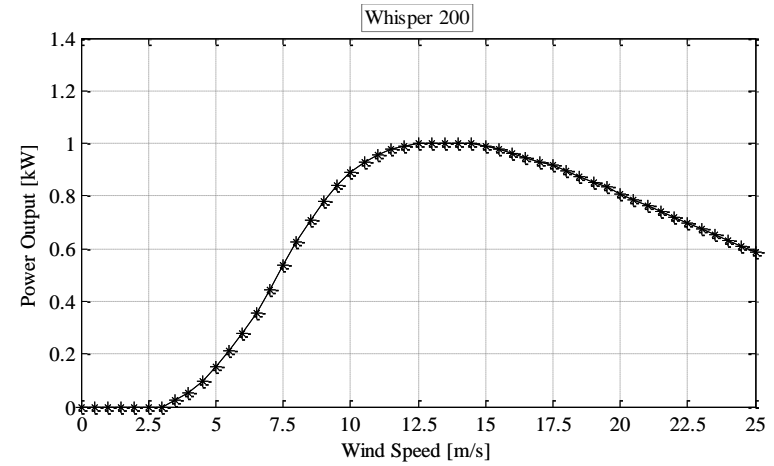
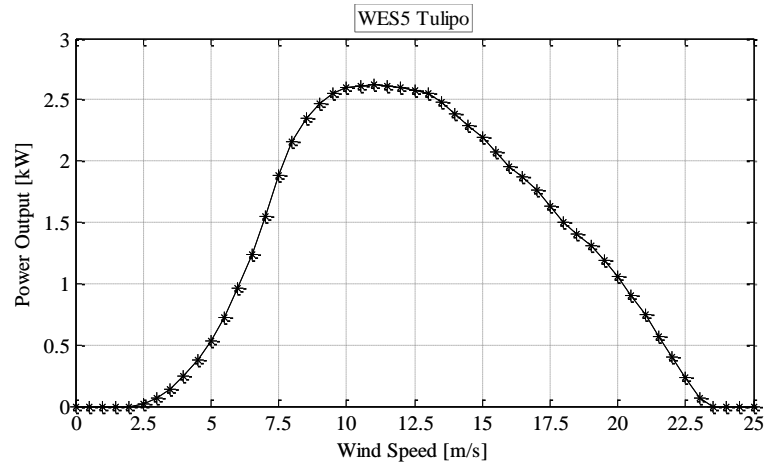


The curve for the Goulds Model VIS Vertical Industrial Submersible Pump.

## Appendix D: Power Curves of Candidate WTGs

[Source: Homer Version 2.67 beta software ([www.nrel.gov/homer](http://www.nrel.gov/homer))]





## Appendix E: MATLAB Program

---

```
%-----  
% Statistical Analysis of Wind Data and Resource Characterization  
%-----  
%  
%-----  
% Variable description  
%-----  
% bws = Borena wind speed [m/s], 72x31 matrix  
% tpc = wind turbine power curves, 232x2 matrix  
% rho = density of surrounding air [kg/m^3]  
% z = height above ground level to get the desired wind speed [m]  
% alpha = friction coefficient (assume the system near the village)  
% zr = reference height, i.e. the height where measurement is taken [m]  
% v_cin = cut-in wind speed of wind turbine [m/s]  
% k = shape parameter  
% c = scale parameter [m/s]  
% std_dev = monthly standard deviation of wind speed [m/s], 12x7 matrix  
% wsd = average monthly wind speed [m/], 12x7 matrix  
% wpd_d = monthly wind power density [W/m^2]  
% wed_d = monthly wind energy density [kWh/m^2]  
% DE = daily energy from wind turbines in decreasing order  
%  
clear all  
clc  
format short g  
%  
%-----  
% input data for parameters  
%-----  
bws=[load('ovrold.dat')]/(24*36); % loading the Borena wind speed  
tpc=load('WTPC.dat'); % loading wind machine power curves  
rho=1.049; % density of surrounding air at 1475m asl  
z=10:5:35; % small-scale towers rang ein height from 20-35m  
alpha=0.25; % assuming the system is near the village  
zr=2;  
v_cin=3; % WTGs cut in wind speed  
effp=0.606; % pump efficiency found using Goulds pump software(ePrism)  
rho_w=1000; % density of water [kg/m^3]  
ga=9.81; % gravitational acceleration [m/s^2]  
H=24; % total dynamic head [m]  
[R N]=size(bws); % R = no of rows of v and N = no of Columns of bws  
shear=(z/zr).^alpha; % computation of wind shear factor  
%  
[mtd vd MTD] = an_nod(R,bws); % function calculating mtd, vd and MTD  
%  
vmean=mean(vd)*shear(1); % mean wind speed at 10m  
vstd=std(vd,1)*shear(1); % std deviation at 10m  
N_v=[4.00;3.9;3.4;2.8;3.4;3.8;4.00;4;3.6;2.9;3.1;3.7]; % NASA ws for Borena  
%  
%-----  
% user input data  
%-----  
disp('The wind data is from 2004 to 2009 and 2010 for ave. results.')
```

---

```
n=input('Enter the year n = '); disp(' ')  
n=n-2003; % the specific year need to analyze  
disp('The height of the hub is 10,15,20,25,30 and 35m.')
```

```

m=input('Enter the hub height m = '); disp(' ')
m=(m/5)-1; % the hub height from the ground
TN=4; % the number which calls p curve values of Skystream 3.7
%
[mws wpd_d wed_d]=d_method(R,mtd,vd,m,rho,shear); % direct method analysis
[tpcs speed pcvs_d]=turbine_pc_interp(tpc,vd,shear,m); % WTG pc interpol.
%
%-----
% statistical method of Calculation
%-----
% NOTE:each column of wsd represent monthly av.wind speed for 2004-2009 and
% overall average monthly wind speed. This values will be processed in
% HOMER software to obtain the hourly wind speed of Borena site.
% Load the data analyzed by HOMER, for data measured at 2m
ws=load('hwsol2.dat'); % adjusted hourly average wind speed data
[hij]= mn_hour(mtd); % estimates the starting and ending hr of each month
%
%-----
% resource characterization monthly power and energy density
%-----

for i=1:7
    for j=1:12 % implies the no of monthes
        hws=shear(1)*ws(hij(j,1):hij(j,2),i); % hourly wind speed over a month
        pm=wblfit(hws); % monthly parameters(k&c)
        fm=wblpdf(hws,pm(1),pm(2));
        ft=sum(fm);
        v_m(j,i)=pm(1)*gamma(1+1/pm(2));
        std_v(j,i)=pm(1)*sqrt(gamma(1+2/pm(2))-(gamma(1+1/pm(2)))^2);
        c(j,i)=pm(1); k(j,i)=pm(2);
    %-----
    % resource characterization monthly power and energy density
    %-----
        wpd_m(j,i)=(rho/(2*ft))*sum(fm.*hws.^3); % @10m [W/m^2]
        wed_m(j,i)=(hij(j,2)-hij(j,1)+1)*wpd_m(j,i)/1000; %@10m [kWh/m^2]
    end
    hwsy(:,i)=shear(1)*ws(:,i); % hourly wind speed over a year
    py(i,:)=wblfit(hwsy(:,i));
    fy(:,i)=wblpdf(hwsy(:,i),py(i,1),py(i,2));
    Ft(:,i)=sum(fy(:,i));
    v_y(i,1)=py(i,1)*gamma(1+1/py(i,2));
    v_y(i,2)=py(i,1)*sqrt(gamma(1+2/py(i,2))-(gamma(1+1/py(i,2)))^2);
    %-----
    % resource characterization yearly power and enegyry
    %-----
        wpd_y(i,:)=(rho/(2*Ft(:,i)))*sum(fy(:,i).*hwsy(:,i).^3); % [W/m^2]
        wed_y(i,:)=8.760*wpd_y(i,:); % [kWh/m^2]
    end
    %
for i=1:7
    hwsy(:,i)=shear(m)*ws(:,i); % hourly wind speed over a year
    py(i,:)=wblfit(hwsy(:,i));
    fy(:,i)=wblpdf(hwsy(:,i),py(i,1),py(i,2));
    Ft(:,i)=sum(fy(:,i));
    v_y(i,1)=py(i,1)*gamma(1+1/py(i,2));
    v_y(i,2)=py(i,1)*sqrt(gamma(1+2/py(i,2))-(gamma(1+1/py(i,2)))^2);
end
%

```

```

%-----
% computation of the most frequent wind speed
%-----
s_dist=[sort(hwsy(:,n)) wblpdf(sort(hwsy(:,n)),py(n,1),py(n,2))];
indices =find(s_dist(:,2)==max(s_dist(:,2)));
most_freq_ws = mean(s_dist(indices ,1));
%
%-----
%computation of percentage of wind speed exceeding cut-in speed
%-----
cc=mean(c(:,n)); % mean value of scale parameter of a year
kk=mean(k(:,n)); % mean value of shape parameter of a year
percentage=100*exp(-(v_cin/cc)^kk);
powerinyr=percentage*87.60; % hours where useful power can be extracted
%
for i=1:6
    for in=1:12
        p_m(in,i)=100*exp(-(5/c(in,i))^k(in,i));% %age of ws exceeding 3m/s
        power_inyr(in,i)=(24/100)*MTD(in,i)*p_m(in,i); % hours in a month
    end
end
%
%-----
% computation of turbine energy production of seven wind turbines
%-----
for ii=1:7 % ii stands for the WTGs
    for j=1:7 % j stands for all annual wind speed data
        Pu(:,ii)=0.5*1000*(wblpdf(speed,py(j,1),py(j,2)).*tpcs(:,ii)); % [W]
        Eu(:,ii)=8.760*Pu(:,ii); % [kWh]
        TP_s(ii,j)=sum(Pu(:,ii)); % av. power of turbine [kW]
        TE_s(ii,j)=sum(Eu(:,ii)); % annual av. energy of turbine [kWh]
    end
end
%
%-----
% computation of capacity factor(C_f)
%-----
p_r=[1 1 3 1.8 2.5 1 3]'; % rated power of wind turbines
C_f=TE_s(:,n)./(8760*p_r); % capacity factor each wind turbines
%
%-----
% water pumping capacity of d/nt wind turbines in the Borena site
%-----
DE=1000*TE_s/365.25; % [Wh]
Q=(effp*DE)/(4*rho_w*ga*H); % daily water flow rate [m^3/s]
Vw=4*3600*Q; % daily water obtained using wind machine [m^3/day]
%
%-----
% monthly output in W and kWh for a wind turbine designated with TN
%-----
for j=1:6
    for i=1:12
        TP_Month(i,j)=0.5*1000*sum(wblpdf(speed,c(i,j),k(i,j)).*tpcs(:,TN));
        TE_Month(i,j)=(24/1000)*MTD(i,j)*TP_Month(i,j);
        TP_Mean(i,1)=mean(TP_Month(i,:));
        TE_Mean(i,1)=mean(TE_Month(i,:));
    end
end
%

```

```

TP_Month=[TP_Month TP_Mean]; % [W]
TE_Month=[TE_Month TE_Mean]; % [kWh]
%
for j=1:7 % "j" is referring to the candidate WTGs
    for i=1:12
        DE_Month(i,j)=1000*TE_Month(i,j)/MTD(i,2); % daily E per month[Wh]
        Q_M(i,j)=(effp*DE_Month(i,j))/(4*rho_w*ga*H); % daily water [m^3/s]
        Vw_M(i,j)=4*3600*Q_M(i,j); % daily water [m^3/day]
    end
end
%
%-----
% performance evaluation of the selected sys as water output
%-----
Q0=effp*8760*1000*tpcs(:,TN)/(4*365.25*rho_w*ga*H); % in [m^3/sec]
V0=Q0*4*3600; % in [m^3/day]
%-----
% water output based on the site wind speed using wind turbine (TN)
%-----
Qm=wblpdf(speed,py(n,1),py(n,2)).*Q0;
Vm=Qm*4*3600; % daily water obtained using wind machine [m^3/day]
%
%-----
% displaying results of some parameters
%-----
disp('Overall average monthly mean wind speed')
disp('-----')
disp('          at 2m          at 10m          at 25m')
disp('          =====          =====          =====')
disp([mws mws*shear(1) mws*shear(5)],disp(' '))
disp('Scale & shape parameters and most frequent wind speed')
disp('-----')
disp('          c [m/s]          k          V [m/s]')
disp('          =====          =====          =====')
disp([py(n,1) py(n,2) most_freq_ws]),disp(' ')
disp('          Distribution parameters')
disp('-----')
disp('          V [m/s]          std dv [m/s]          c[m/s]          k')
disp('          =====          =====          =====          =====')
disp([v_m(:,n) std_v(:,n) c(:,n) k(:,n) ]),disp(' ')

disp('WPD and WED using statistical method @ 10m')
disp('-----')
disp('          P [W/m^2]          E [kWh/m^2]')
disp('          =====          =====')
disp([wpd_m(:,n) wed_m(:,n)]),disp(' ')
%
disp('Turbine Production using statistical method')
disp('-----')
disp('Wind turbine          Energy [kWh] ')
disp('=====          =====')
disp(['BWCXL.1          ',num2str(TE_s(1,n))])
disp(['Generic 1kW          ',num2str(TE_s(2,n))])
disp(['Generic 3kW          ',num2str(TE_s(3,n))])
disp(['SkyStream3.7          ',num2str(TE_s(4,n))])
disp(['WES5 Tulipo          ',num2str(TE_s(5,n))])
disp(['Whisper 200          ',num2str(TE_s(6,n))])
disp(['Whisper 500          ',num2str(TE_s(7,n))]),disp(' ')
%

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```

disp('Capacity factor of wind turbines')
disp('-----')
disp('Wind turbine   C_f ')
disp(' =====')
disp(['BWCXL.1       ',num2str(C_f(1))])
disp(['Generic 1kW   ',num2str(C_f(2))])
disp(['Generic 3kW   ',num2str(C_f(3))])
disp(['SkyStream3.7  ',num2str(C_f(4))])
disp(['WES5 Tulipo    ',num2str(C_f(5))])
disp(['Whisper 200    ',num2str(C_f(6))])
disp(['Whisper 500    ',num2str(C_f(7))]),disp(' ')
%
disp('Wind turbine type and possible flow rate')
disp('-----')
disp('Wind turbine     m^3/day')
disp(' =====')
disp(['BWCXL.1         ',num2str(Vw(1))])
disp(['Generic 1kW     ',num2str(Vw(2))])
disp(['Generic 3kW     ',num2str(Vw(3))])
disp(['SkyStream3.7    ',num2str(Vw(4))])
disp(['WES5 Tulipo     ',num2str(Vw(5))])
disp(['Whisper 200     ',num2str(Vw(6))])
disp(['Whisper 500     ',num2str(Vw(7))]), disp(' ')
disp('NOTE: Unless specified the results are based')
disp('on the input hub height and the respective year!'),disp(' ')
%
% -----
% different plots of the results
% -----
set(0,'defaultAxesFontName','Times New Roman')
set(0,'defaultTextFontName','Times New Roman')
set(gca,'FontSize',12) % adjusts the axes font size
set(0,'defaultAxesLineWidth',2)
set(0,'defaultLineLineWidth',1.5)
% -----
% monthly mean wind speed for three cases
% -----
plot(0.5:11.5,mws,'-dk','MarkerEdgeColor','k','MarkerFaceColor','m',...
     'MarkerSize',6), hold on
plot(0.5:11.5,mws*shear(1),'-sk','MarkerEdgeColor','k','MarkerFaceColor'...
     , 'r','MarkerSize',6), hold on
plot(0.5:11.5,N_v,'-vk','MarkerEdgeColor','k','MarkerFaceColor','g',...
     'MarkerSize',6)
xlabel('Months'), ylabel('Mean Wind Speed [m/s]')
set(gca,'XTickLabel',{'Jan','Feb','Mar','Apr','May','Jun','Jul','Aug',...
                    'Sep','Oct','Nov','Dec'})
set(gca,'XTick',0.5:11.5), ylim([0 (1+max(mws*shear(m))]))
legend('Measured at 2m','Calculated at 10m','NASA data at 10m');
grid on, hold off, pause
% -----
% plots of various parameters
% -----
plot(mean(vd)*([0:50]/zr).^alpha,0:50,'k')
xlabel('Wind speed [m/s] ')
ylabel('Height above ground [m]')
set(gca,'XTick',0:0.5:6), grid on, hold off, pause
plot([0;sort(hwsy(:,n))],[0;100*wblpdf(sort(hwsy(:,n)),py(n,1),py(n,2))],'k')
xlabel('Wind Speed [m/s]')
ylabel('Weibull Probability Density [%]')

```

```

set(gca,'XTick',0:2:25),set(gca,'YTick',0:2:22), grid on, hold off, pause
plot([0;sort(hwsy(:,n))],[0;100*wblcdf(sort(hwsy(:,n)),py(n,1),py(n,2))],'k
')
xlabel('Wind Speed [m/s]')
ylabel('Weibull Cummulative Density [%]')
set(gca,'XTick',0:2:25)
grid on, hold off, pause
% -----
% wind power and energy density plots
% -----
bar(1:12,wpd_m(:,n),0.3,'k'), hold on % WPD(s.method) for n and @10m
xlabel('Months'), ylabel('Power Density [W/m^2]')
set(gca,'XTickLabel',{'Jan','Feb','Mar','Apr','May','Jun','Jul','Aug',...
'Sep','Oct','Nov','Dec'}), grid on, hold off, pause
bar(1:12,wed_m(:,n),0.3,'b'), hold on % WED(s.method) for n and @10m
xlabel('Months'), ylabel('Energy Density [kWh/m^2]')
set(gca,'XTickLabel',{'Jan','Feb','Mar','Apr','May','Jun','Jul','Aug',...
'Sep','Oct','Nov','Dec'}), grid on, hold off, pause
% -----
% energy harnessed with the wind machines
% -----
set(0,'defaultAxesLineWidth',3)
set(0,'defaultLineLineWidth',3)
plot(speed,Eu(:,1),'-dk','MarkerEdgeColor','k','MarkerFaceColor','k'...
,'MarkerSize',10), hold on
plot(speed,Eu(:,2),'-sk','MarkerEdgeColor','k','MarkerFaceColor','w'...
,'MarkerSize',10), hold on
plot(speed,Eu(:,3),'-vk','MarkerEdgeColor','k','MarkerFaceColor','w'...
,'MarkerSize',10), hold on
plot(speed,Eu(:,4),'-sk','MarkerEdgeColor','k','MarkerFaceColor',...
'g','MarkerSize',10), hold on
plot(speed,Eu(:,5),'-vk','MarkerEdgeColor','k','MarkerFaceColor',...
'r','MarkerSize',10), hold on
plot(speed,Eu(:,6),'-ok','MarkerEdgeColor','k','MarkerFaceColor',...
'y','MarkerSize',10), hold on
plot(speed,Eu(:,7),'-dk','MarkerEdgeColor','k','MarkerFaceColor',...
'y','MarkerSize',10), hold on,
xlabel('Wind Speed [m/s]')
ylabel('Energy Harnessed [kWh]')
set(gca,'XTick',0:2.5:25), set(gca,'YTick',0:100:800)
legend('BWCXL.1','Generic 1kW','Generic 3kW','SkyStream 3.7',...
'WES5 Tulipo','Whisper 200','Whisper 500');
grid on, hold off, pause
% -----
% possible flow rates of water with seven wind turbines
% -----
set(0,'defaultAxesLineWidth',2)
set(0,'defaultLineLineWidth',1.5)
bar(1:7,sort(Vw(:,n),'descend'),0.25,'b') % a pump working for 6 hrs a day
set(gca,'XTickLabel',{'WES5 Tulipo','Whisper 500','SkyStream 3.7',...
'Generic 3kW','Whisper 200','BWCXL.1','Generic 1kW'})
set(gca,'YTick',0:25:(max(Vw(:,n))+5)), set(gca,'ylim',[0
(max(Vw(:,n))+5)])
xlabel('Wind Turbine Type'), ylabel('Water Output [m^3/day]')
grid on, hold off, pause
% -----
% plots of daily water output over each month
% -----
bar(1:12,Vw_M(:,TN),0.3,'k'), grid on
set(gca,'XTickLabel',{'Jan','Feb','Mar','Apr','May','Jun','Jul','Aug',...

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        'Sep', 'Oct', 'Nov', 'Dec'}), grid on
set(gca, 'YTick', 0:50:(max(Vw_M(:,TN))+5))
set(gca, 'ylim', [0 (max(Vw_M(:,TN))+5)])
xlabel('Months'), ylabel('Water Output [m^3/day]')
grid on, hold off, pause
% -----
% plots of water output vs wind speed
% -----
plot(2.5:0.5:12, Vm(6:25), '-ok', 'MarkerEdgeColor', 'k', 'MarkerSize', 8)
set(gca, 'XTick', 2:12),
set(gca, 'YTick', 0:1:(max(Vm(6:25))+2))
xlabel('Wind Speed [m/s]')
ylabel('Water Output [m^3]')
grid on, pause
% -----
% plots of performance evaluation
% -----
bar(speed, V0, 0.3, 'k'), grid on
set(gca, 'XTick', 0:2.5:25),
set(gca, 'YTick', 0:100:(max(V0)+5)), title('Whisper 500')
xlabel('Wind Speed [m/s]'), ylabel('Water Output [m^3/day]')
grid on, hold off, pause
% -----
% plots of average hourly wind speed over a month at 25m
% -----
for j=1:12
    plot([hij(j,1):hij(j,2)], shear(m)*ws(hij(j,1):hij(j,2),n), 'k')
    set(gca, 'XTick', [(hij(j,1)-1):48:hij(j,2)])
    set(gca, 'YTick', [0:2:max(shear(m)*ws(hij(j,1):hij(j,2),n))+2])
    xlabel('Hour [hour]')
    ylabel('Wind Speed [m/s]')
    if j==1, title('January'), elseif j==2, title('February'),
        elseif j==3, title('March'), elseif j==4, title('April'),
        elseif j==5, title('May'), elseif j==6, title('June'),
        elseif j==7, title('July'), elseif j==8, title('August'),
        elseif j==9, title('September'), elseif j==10, title('October'),
        elseif j==11, title('November'), elseif j==12, title('December'),
    end
    grid on, pause
end
% -----
% plots of hourly wind speed in a year
% -----
plot(1:8760, shear(m)*ws(:,n), 'k', 'LineWidth', 1.0)
xlabel('Hour [hr]')
ylabel('Wind Speed [m/s]')
grid on

```