Assessment of Feasibility of Wind Pumping For Village Water Supply and Irrigation in Ethiopia

By

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A thesis submitted to the School of Graduate Studies of Addis Ababa University in partial fulfillment of the requirements of the Degree of Masters of Science in Mechanical Engineering (Thermal Engineering Stream)

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Abstract

In this project three consecutive years wind speed data measured five times a day for more than thirteen stations from NMSA is used to predict the wind distribution pattern of the country. Based on the day time data, the most probable night time data is generated using appropriate software (HOMER), hence year round hourly data is generated for all stations along with statistical wind distribution model weibull shape and scale parameters. Based on the wind potential assessment, wind pumping feasibility is done for water supply and irrigation for a hypothetical model community at three different locations having similar topography as that of the representative sites. For pre determined daily water demand and varied water well depth, wind pump sizing is done for each application.

Following the technical feasibility, economic analysis is done to compare with that of diesel pumping system. Cost analysis model is prepared using excel, in which system sizing and cost estimation are done. The life cycle cost, break even and unit water cost at different delivery head for pre determined daily flow rate is calculated based on given financial parameters for both systems. The unit water cost for wind pumping and diesel pumping at typical delivery head of 20m for mekele, Jijiga and Assosa are found as 5.66, 6.71 and 7.01birr/m^3 respectively, where as diesel pumping costs 25.10birr/m^3. In addition breakeven for wind pumping at typical delivery head of 20m occurs 1.9 years after the system becomes operational. Hence, the result shows that wind pumping is found to be more economical for water supply and irrigation than diesel pumping for stations having average wind speed 2.5m/s and above in the critical month.

In general at low hydraulic load wind pumping is best economical than diesel pumping for monthly average wind speed 2.5m/s and greater in the critical month. In this regard, the country wind potential assessment shows average monthly and annual wind speed above 2.5m/s is found extensively in Ethiopia, which strengthens the feasibility of wind pumping in the country.

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Abbreviations

NMSA	Ethiopian National Metrological Service Agency
WP	Wind water pumping
DP	Diesel water pumping

CHAPTER 1

1.1 Motivation

Almost energy is the primary and most universal measure of all kind of work by human beings and nature. Everything in the world is the expression of flow of energy in one of its forms. The energy resources available can be divided into three types. These are primary energy sources (coal, oil, natural gas, uranium) which provide a net supply of energy, secondary energy sources (solar energy, wind energy, water energy) and supplementary energy sources (geothermal, ocean thermal).

Energy is an important input in all sectors of any country's economy. The standard of living of any given country can be directly related to per capita energy consumption.

Energy crisis is due to the rapid growth of world population and the improved standard of living of human beings. The per capita energy consumption is a measure of the per capita income or it is a measure of the prosperity of the nation.

Developing countries, like Ethiopia, at present show great motivation towards renewable resources. Wind energy is one of these renewable resources. Previous wind assessment on wind potential in Ethiopia shows an indication on potential of wind for water pumping in Ethiopia.

In this regard, the development of wind pumping will improve the welfare, health and safety of rural population by providing sustainable water supply system and the conservation of fossil energy used by diesel/petrol water pumps, consequently preserving the environment in particular with respect to its high potential to contribute to the reduction of the CO_2 emissions.

1.2 Background of the study

Ethiopia is a Federal Democratic Republic (FDRE) since 1991 with nine Regional States and two Municipality Administrations. With an estimated population of 75 million and 113 million hectares of landmass, Ethiopia is one of the Horn of African countries located between 33^0 and 48^0 East longitudes and between 3^0 and 15^0 North latitude. It has a diverse climatic condition due to the contrasting altitude, which ranges from the highest point of 4650 meters above sea level at Ras Dashen Mountain to 420 meters below sea level at Dallol Depression.

In Ethiopia, like in most developing African countries, the energy sector is dominated by traditional energy. Modern energy, electricity, petroleum, and infrastructure for energy supply exist mainly in urban areas. For this reason, majority of the population living in rural areas have little access to modern energy.

In most of rural areas of our country Ethiopia, traditional animal power and manpower is still used for lifting water for crop irrigation or for drinking purposes. Both these methods are highly inefficient and time consuming. The energy requirement of rural people in Ethiopia is quite low and is met largely by non-commercial energy sources like firewood, agricultural wastes and cow dung cakes and in this regard efforts are being made in Ethiopia for provide electricity in rural areas but the progress has been slow mainly due to the reason that it is capital intensive and is difficult to connect remote scattered villages with the central electric grid system. Therefore decentralized energy system like wind and solar/PV/ powered pump sets may be more appropriate for meeting the water supply demand.

The agricultural land is either irrigated by natural means like rain or by using animal or muscle power and the same is true for household application. The use of diesel or petrol operated water pumping sets or is also increasing which has its own drawback in fuel cost and CO_2 emission. As various studies on renewable energy sources shows, Ethiopia has a large potential wind energy is the one. Wind pumping for village water supply was in use in some parts of Ethiopia since 1970s. However it was not disseminated in sufficient scale to rural areas where most of the population lives. Moreover, the installation was not based taking care for detail work on the design and considering feasibility study. In addition, as the demand with the increase in population, more land is to be brought under cultivation to increase crop production for meeting the demand for food, for which water is an essential ingredient.Hence,more energy for pumping of water for irrigation and drinking is required.

This thesis focuses on the feasibility of wind pumping for village water supply and irrigation in comparison with diesel/petrol water pumping and to recommend where wind water pumping can be used in different parts of Ethiopia.

1.3 Objective of the Study

Ethiopia is endowed with abundant renewable energy sources, The major objective of this thesis is to make assessment on the wind potential of the country based on measured 17 synoptic and 18 secondary stations in different parts of the country, from Ethiopia national metrological Service Agency(NMSA) and the feasibility of wind water pumping for village water supply and irrigation in comparison to diesel/petrol water pumping by developing an integrated wind turbine and piston pump model for determination of cost of water pumping per m^3 for selected sites, and to forward recommendation on areas where wind pump can be used.

1.4 Methodology

First of all literature review of relevant materials on wind potential assessment in Ethiopia and application of windmills for water pumping is conducted. The literatures are mainly from electronic media, journals from Science direct and books from the library. Then, Wind data's are collected from NMSA of Ethiopia. Generation of hourly wind speed to fill the night time data is done using HOMER software, following these wind pump feasibility is done for a model community of 500 populations at selected four stations by comparing with that of diesel pumping for water supply and irrigation. Cost and financial analysis is done after Cost modeling sheet is prepared using Excel. Finally conclusion and recommendation are made.

CHAPTER 2

2. Literature Survey

2.1 Basics of Wind Energy

The earth receives around 1.7x10^{14} kW of power from the sun in the form of solar radiation. This radiation heats up the atmospheric air. The intensity of this heating will be more at the equator (0^{o} latitude) as the sun is directly overhead. Air around the poles gets less warm, as the angle at which the radiation reaches the surface is more acute. The density of air decreases with increase in temperature. Thus, lighter air from the equator rises up into the atmosphere to a certain altitude and then spreads around. This causes a pressure drop around this region, which attracts the cooler air from the poles to the equator. This movement of air causes wind.

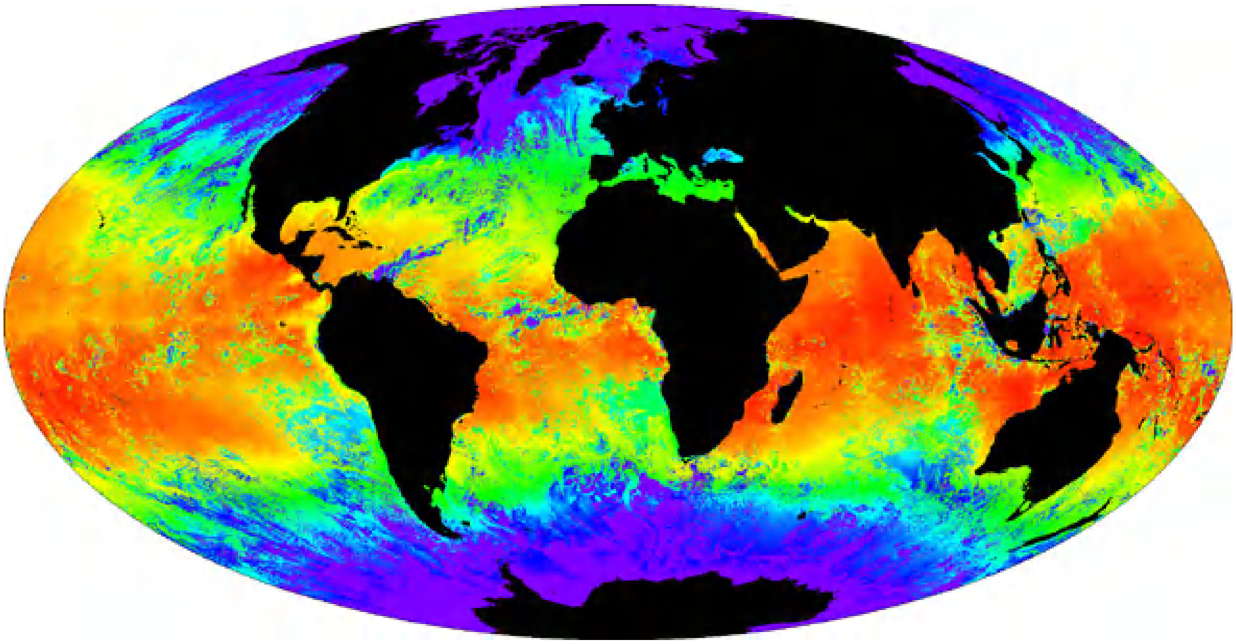


Figure 2-1: NASA satellite Sea surface temperature image of the global map [source: NASA images]

Thus, the wind is generated due to the pressure gradient resulting from the uneven heating of earth's surface by the sun. As the very driving force causing this movement is derived from the sun, wind energy is basically an indirect form of solar energy. One to two per cent of the total solar radiation reaching the earth's surface is converted to wind energy in this way. The wind described above, which is driven by the temperature difference, is called the geotropic wind, or more commonly the global wind. Global winds, which are not affected by the earth surface, are found at higher altitudes. The rotation of earth leads to another phenomenon near its surface called the Coriolis Effect, named after the famous mathematician Gustavo Gaspar Coriolis. Due to the Coriolis Effect, the straight movement of air mass from the high pressure region to the low pressure region is diverted. Under the influence of Coriolis forces, the air move almost parallel to the isobars. Thus, in the northern hemisphere, wind tends to rotate clockwise where as in the southern hemisphere the motion is in the anti-clockwise direction [5].

2.2 Wind Measurement and Instruments

As the power is sensitive to the wind speed, good quality measuring instruments which are sensitive, reliable and properly calibrated should be used for wind measurements. Some of popular measuring instruments will be described below:

2.2.1 Cup Anemometers

The anemometer, most commonly used in wind energy measurements is the cup anemometer. It consists of three (or four) equally spaced cups attached to a centrally rotating vertical axis through spokes. The cups are hemispherical or conical in shape and made with light weight material. This is basically a drag device.

Figure 2-2: Cup Anemometer

When kept in the flow, the wind exerts drag force on the cups. As the drag coefficient of concave surface is more than on the convex surface, the cup with its concave side facing the wind experiences more drag force. This causes the cups to rotate on its central axis. The intensity of rotation is directly proportional to the velocity of incoming wind. This is further calibrated in terms of wind velocity, which can be directly sensed and recorded.

Although these anemometers can sustain a variety of harsh environments, they have some limitations. One major problem is that due to their inertia, cup anemometers do not register lower wind speeds at starting. Further, there is an over-speeding effect, because the anemometer caused by aerodynamic properties, reacts quicker to increase in wind velocity than to decrease. This can lead to over estimation of the mean wind speed in gusty situations due to the fact that they accelerate more quickly than they decelerate. Nevertheless of these limitations, cup anemometers are widely used for measuring wind velocity in meteorological as well as wind energy applications. The same equipment is used in Ethiopian metrological stations.

2.2.2 Sonic Anemometer

Sonic anemometers measure the wind velocity by sensing the changes in the speed of sound in air(wave speed). It has three arms, mounted perpendicular to each other, as shown in Figure below. Transducers fitted at the tips of each arm emit acoustic signals which travel up and down through the air. Speed of sound in moving air is different from that through still air.

Figure 2-3: Sonic Anemometer

Let V_s be the velocity of sound in still air and V is the wind velocity. If both the sound and wind are moving in the same direction, then the resultant speed of sound waves (V_1) is $V_1=V_s+V$.Similarly, if the propagation of the sound waves is opposite to the wind direction, then the resultant velocity of sound (V_2) is $V_2=V_s-V$.Combining the two equations we get $V= (V_1-V_2)/2$ .Thus, by measuring the speed of sound waves between the transducer tips during its upward and downward travel, the wind velocity can be estimated. Sonic anemometers also do not have any moving parts. They are reliable and accurate for measuring wind velocity in the range of 0 to 65 m/s. However, they are costlier than the other types of anemometers.

2.3.3 Wind Measuring Stations in Ethiopia

Meteorology in Ethiopia first attained its importance in aviation, and a small meteorological unit was established in 1951 with in the Civil Aviation Department (now Civil Aviation Authority) to cater services solely for aeronautical purposes. As the other socio-economic sector slowly began to realize the importance of meteorological information and advice for their respective activities, requests began to flow into this small unit. Thus, the unit promoted to National Meteorological Agency, as an autonomous government organization, by December 1980. Since then, it has reorganized itself at different times to meet the growing demand in meteorological services from diversified socio-economic sectors.

The Agency has currently four groups of stations Principal, Synoptic, Ordinary and Rainfall recording stations.

***Principal Stations*:** These are stations at which meteorological observations are made for climatological purposes. Observations are taken every three hours in the following GMT times **(03:00, 06:00, 09:00, 12:00, and 15:00 GMT).** There are more than 150 Principal stations in Ethiopia.

***Synoptic Stations*:** These are station at which meteorological observations are made for the purposes of synoptic meteorology. Observations are taken every hour for 24 hours a day at full GMT hours. There are 22 Synoptic stations in Ethiopia, according to the Agency website. But what is available actually is same as Principal stations except the additional **18:00 GMT** data

Ordinary Stations*:** These are stations at which only three meteorological elements are observed, i.e. maximum air temperature of the day, minimum air temperature of the day and total rainfall amount in 24 hours. Observations are taken at ***06:00 and ***15:00 GMT.***

Rainfall Recording Stations*:** These are stations at which only the total rainfall amount in 24 hours are observed. Observations are taken at ***06:00 GMT.

2.3 Previous Wind Potential Studies in Ethiopia

The total wind resource of Ethiopia is estimated at 20.064 million TJ/year [7]. Wind energy is one of the resources which is virtually unexploited in Ethiopia. Only periodic attempts were made by a few organizations to harness this free and inexhaustible source of energy. Studies conducted on the wind resource potential in Ethiopia shows as there is sufficient wind potential for power generation and wind pumping activities in most part of the country. The study conducted by [W. Wolde-Ghiorgis W, 1987] over 20 typical stations in the country shows annual mean wind speed above 2.8m/s is obtained in most of the stations, and shows wind potential areas on map with approximate isovents.

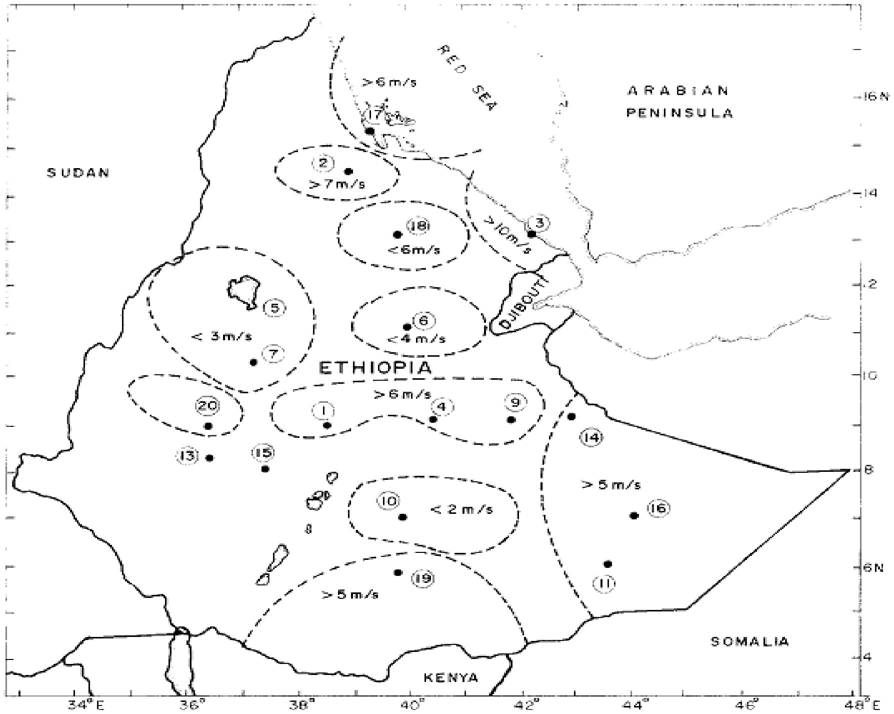


Figure 2-4: Map of Ethiopia with wind data stations and approximate isovents at 10m level [W. Wolde-Ghiorgis W, 1987]

The other study conducted by [F.Drake and Y.Mulugetta, 1996][12] in over 80 stations in the county and boarder cities. Out of the 80 stations 21 stations have hourly data measured three times a day and 60 stations have only monthly average. From these study it shows as the available wind energy in Ethiopia is highly variable both spatially and temporarily. The general trend of the wind distribution shows a west-east and south-north increase of wind energy distribution, The high land regions exhibit high during dry season and relatively calm condition during rainy season. Whereas the low land regions towards the east reveal the reverse pattern with the winter and summer periods characterized by low and high wind regimes respectively.

In addition to the above studies two studies [G.Bekele, Björn Palm, 2008][5] conducted wind potential assessment on selected four typical locations (Addis Ababa, Debrezit, mekele and Nazareth) with recent three year consecutive wind speed data from NMSA.In the assessment different assumptions are considered to fill the night time data, as the measured data is only day time data recorder five times a day with three hour interval. The most probable wind speed in the regimes is generated by using HOMER software with some advanced input parameters and monthly averages from the measured day time data. The night time wind speed is generated from day time data, by stretching the three hour interval in to five hour over a day.

Based on the studies conducted by the references quoted [9] and [12] most of wind measuring stations in Ethiopia have annual average greater than 2.5m/s at reference height of 10m.

2.4 Basics of Wind energy Conversion Technology

Energy available in wind is basically the kinetic energy of large masses of air moving over the earth's surface. Blades of the wind turbine receive this kinetic energy, which is then transformed to mechanical or electrical forms, depending on the end use. The efficiency of converting wind to other useful energy forms greatly depends on the efficiency with which the rotor interacts with the wind stream

2.4.1 Power Available in Wind Spectra

The kinetic energy of a stream of air with mass m and moving with a velocity V is given by

$$E(V) = \frac{1}{2} m V^2 \qquad 2.1$$

Consider a wind rotor of cross sectional area A exposed to this wind stream as shown in Figure 2.5 below. The kinetic energy of the air stream available for the turbine can be expressed as

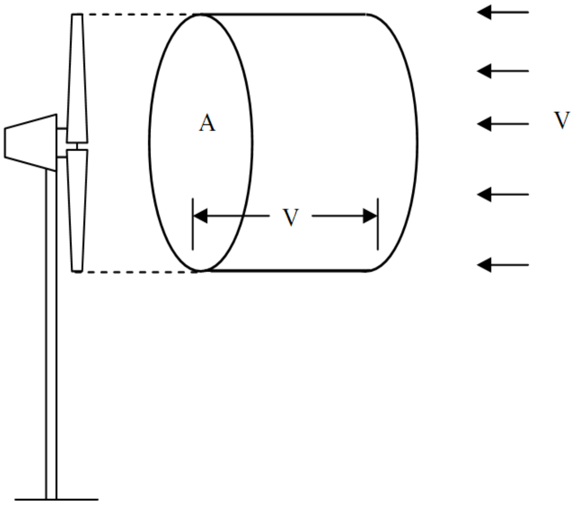


Figure 2-5: An air parcel moving towards a wind turbine[4]

$$E(V) = \frac{1}{2}\rho_a v V^2 \qquad 2.2$$

Where ρ_a is the density of air and v is the volume of air parcel available to the rotor. The air parcel interacting with the rotor per unit time has a cross-sectional area equal to that of the rotor (A_T) and thickness equal to the wind velocity (V). Hence energy per unit time, that is power, can be expressed as

$$P = \frac{1}{2}\rho_a A_T V^3 \qquad 2.3$$

From eq 2.3, it can be seen that the factors influencing the power available in the wind stream are the air density, area of the wind rotor and the wind velocity. Effect of the wind velocity is more prominent owing to its cubic relationship with the power.

If the elevation Z and temperature T at a site are known, then the air density is given by

$$\rho_a = \frac{353.049}{T} e^{(-0.034\frac{Z}{T})} \qquad 2.4$$

At ambient temperature of 20°C, the effect of elevation on density is shown below.

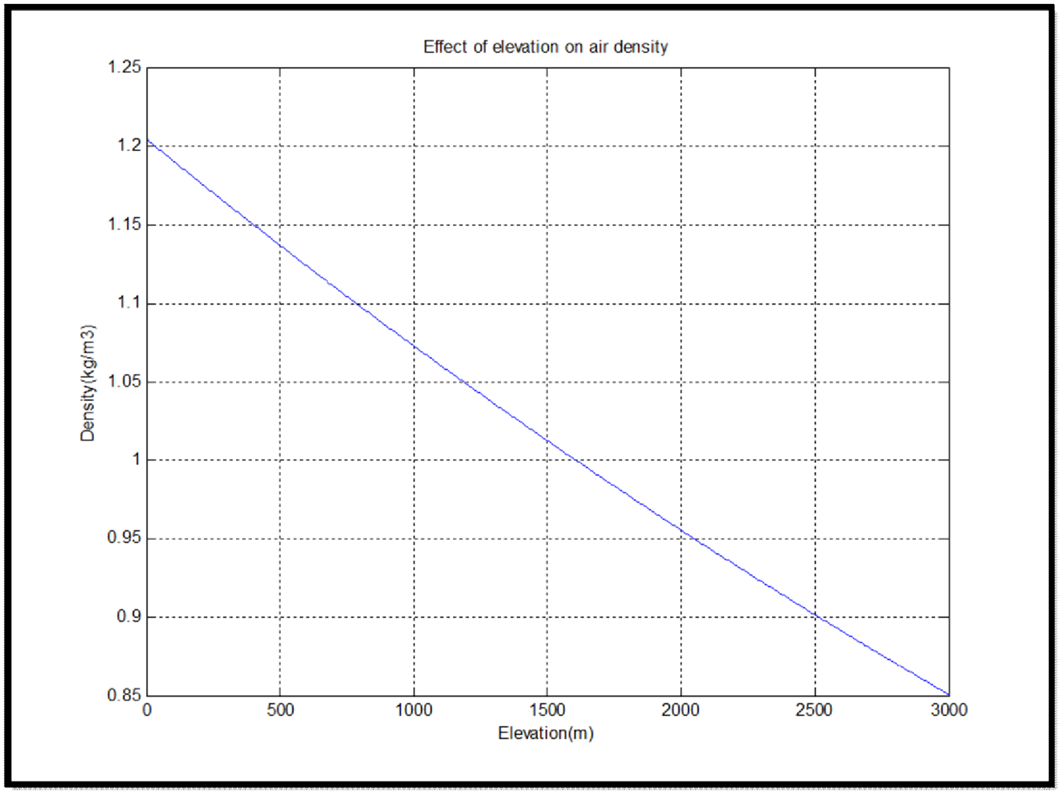


Figure 2-6: Effect of elevation on air density at ambient temperature of 20°C

The density of air decreases with the increase in site elevation as illustrated in Figure 2.6. The same is true for temperature. Due to this relatively low density, wind is rather a diffused source of energy. Hence large sized turbines are often required for substantial power production. Hence, the most prominent factor deciding the power available in the wind spectra is its velocity. When the wind velocity is doubled, the available power increases by 8 times. In other words, for the same power, rotor area can be reduced by a factor of 8, if the system is placed at a site with double the wind velocity. In this regard, selecting the right site plays a major role in the success of a wind power projects.

2.4.2 Wind Shear

The flow of air above the ground is retarded by frictional resistance offered by the earth surface (boundary layer effect). This resistance may be caused by the roughness of the ground itself or due to vegetations, buildings and other structures present over the ground. Theoretically, the velocity of wind right over the ground surface should be zero and velocity increases with height up to a certain elevation. The rate at which the velocity increases with height depends on the roughness of the terrain. Presence of dense vegetations like plantations, forests, and bushes slows down the wind considerably. Level and smooth terrains do not have much effect on the wind speed. The surface roughness of a terrain is usually represented by the roughness class or roughness height. The roughness height of a surface may be close to zero (surface of the sea) or even as high as 2 (town centers).

Some typical values are 0.005 for flat and smooth terrains, 0.025-0.1 for open grass lands, 0.2 to 0.3 for row crops, 0.5 to 1 for shrubs and 1 to 2 for forests, town centers etc.

Wind speed near the ground changes with height. This requires an equation that predicts the wind speed at one height in terms of the measured speed at another.

The wind data available at meteorological stations might have been collected from different sensor heights. In most of the cases, the data are logged at 10 m as per recommendations of the World Meteorological Organization (WMO). In wind energy calculations, the concern is the velocity available at the rotor height. The data collected at any height can be extrapolated to other height on the basis of the roughness height of the terrain. Due to the boundary layer effect, wind speed increases with the height in a logarithmic pattern. If the wind data is available at a reference height Z_r and the roughness height is Z_0, then the velocity up to 60 m at the same location can be estimated at a height Z by the relation

$$\frac{v(z)}{v(z_r)} = \frac{\ln(z/z_0)}{\ln(z_r/z_0)} \qquad 2.5$$

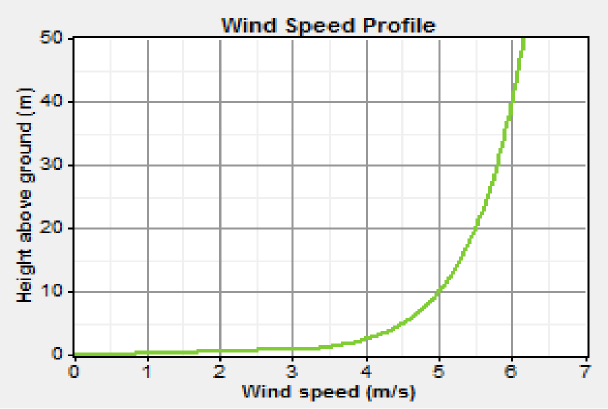


Figure 2-7: Typical wind speed profile for roughness length of 0.01[Source: HOMER]

2.4.3 Wind Rose

Information on the velocity and direction of wind, in a combined form, can be presented in wind roses. The wind rose is a chart which indicates the distribution of wind in different directions. The chart is divided into 8, 12 or even 16 equally spaced sectors representing different directions. Three types of information can be presented in a wind rose. (1) The percentage of time for which wind from a particular direction is received. This can show the direction from which most of the wind is obtained. (2) The product of this percentage and the average wind velocity in this direction. This indicates the average strength of the wind spectra. (3) The product of time percentage and cube of the wind velocity. This helps in identifying of the energy available from different directions.[2]

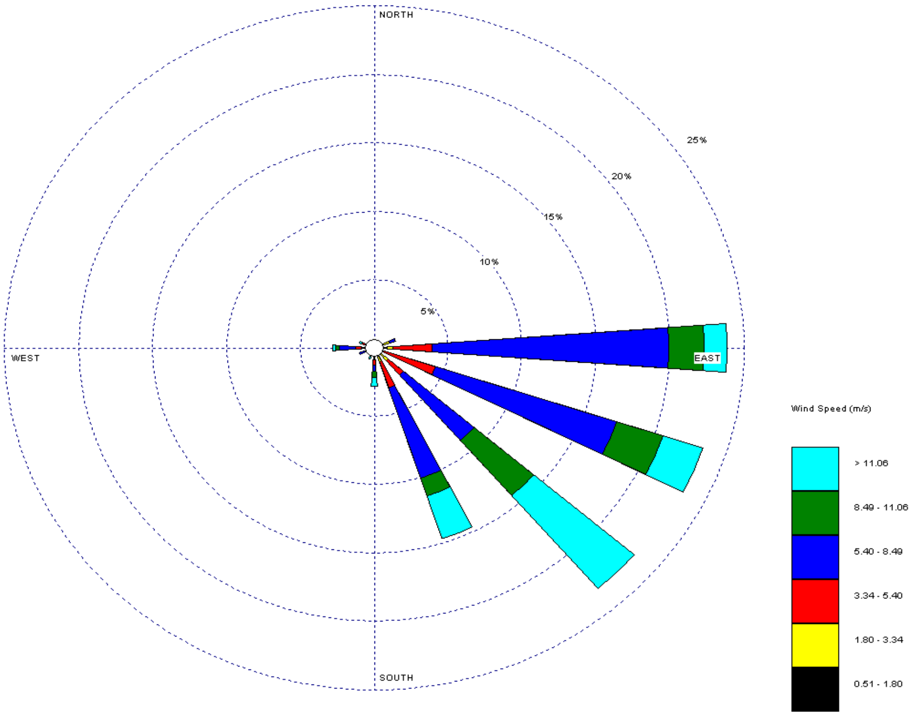


Figure 2-8: Wind-rose diagram of Mekele for the month of April

Based on 1982-2003 data at 1200 GMT[Source:NMSA]

2.5 History of Windmills for Water Pumping

Water is a basic need for mankind, be it for domestic purposes, for livestock or for irrigation. In many rural areas of the world, water has to be lifted from rivers and wells using some kind of pumping system.

For several centuries in Europe, and during the 19th century in the United States, wind energy was widely used to pump water. Historically, wind energy was first used to propel boats through rivers and across oceans. The idea of the sail, which captures the wind, was then adapted for use on land, and windmills were built to mill flour. In Europe, the earliest record of horizontal axis windmills goes back to the 12th century in England. The technology spread all over Europe in subsequent centuries. [1]

In Holland, from the 15th century onwards, windmills were used to drain swamps and lakes and reclaim new lands. Wind energy was used to lift water and pump it out of an area. By reclaiming low-lying land for agriculture, windmills contributed greatly to Holland's economic development. By the beginning of the 19th century there were about 10,000 large windmills with rotor blades up to 28 meters in diameter in operation in that country. In the rest of Europe there were several tens of thousands more, used for a number of purposes.

Use of windmills declined in Europe following the introduction of steam engines. But as European mills began to disappear, a different type of windmill entered into wide use on the Great Plains of the U.S. The multibladed "American" wind pump was developed, consisting of rotor blades to catch the wind, a transmission to transfer the energy to a piston pump, and the pump itself, which raised the water. Millions of these wind mills were used to pump water for domestic use and for livestock. They were essential to the rapid development on the plains. Many of these windmills fell into disuse when they were replaced by oil-powered or electric pumps.

Though the use of windmills in the industrialized countries has now greatly declined, it has not stopped. The classic multibladed windmill is still being manufactured and probably about 4 million are in use today worldwide, particularly in the U.S., Argentina, Australia and South Africa. They provide water for households, for livestock, and sometimes for irrigation.

2.6 Ethiopian Experience of Windmills for Water Pumping

In 1973, the American Presbyterian mission around Omo in southern region carried "Food from Wind Project" and had used a series of locally manufactured Cretan Sail windmills for irrigating small plots of land on the banks of the Omo River. Followed by this, former Ethiopian Water Resource Authority (EWRA) had imported and installed few commercial multi-bladed windmills in the rift valley basin, but many of these windmills were either blown down by severe storms or damaged due to lack of proper follow up and maintenance, as per the author. [8]

Figure 2-9: Mechanical wind pump [Source: Poldaw specification]

The other main organization that is engaged in wind pumping technology in Ethiopia was Lay Volunteers International Association (LVIA). It is based in Meki and engaged in partially manufacturing multi-bladed wind pumps with rotor diameters of 5 and 6 metres locally. Some components of these units are produced in Addis Ababa, others are fabricated in Meki and a few components are imported from Italy. Similar to the other organizations, the density of installation of these water abstraction devices is highest in the Rift Valley basin. [8]

One of local private company Equatorial Business Group(EBG) also up to now is engaged on manufacturing and testing of a 6 meter rotor diameter multi bladed wind pump in its Energy Division. This wind pump is mainly based on Tozzi and Bardi's design, an Italian wind pump manufacturer employing both casting and welding technologies. Orientation of the rotor into the wind is realized by a spring loaded tail vane, while the over-speed control is achieved by eccentrically positioning the rotor axis from the tower centre. The manufacturing of these mills is done partly in EBG's own workshop and by sub-contracting other workshops for components that require special purpose machines.

As the several attempts in manufacturing wind pumps locally shows, wind pumps can be manufactured in small engineering workshops in Ethiopia. The attempt has also shown that manufacturing of a product need not necessarily be carried out within one shade. By combining the skilled manpower and machinery of different organizations, high quality products can be manufactured locally.

2.7 Typical Water Pumping Applications

Wind pumps are used to pump water for a variety of applications. Some of these are as follows:

- Domestic water supply
- Water supply for livestock
- Irrigation
- Drainage
- Salt ponds
- Fish farms

Depending on the type of application, different kinds of systems can be used. The size of mechanical wind pumps runs from 1.2 to 6 m diameter. Depending on the pumping height and average wind speeds, the average power output ranges from a few watts to about 1 kW. For higher power demands wind electric pumping systems (WEPS) can be applied, incorporating a wind generator (available in larger diameter) driving an electric motor-pump combination through an electrical transmission. They are already in incidental use in developing countries for average power outputs of up to 10 kilowatts. There is no reason why such systems could not be technically and economically feasible for power outputs of tens of kilowatts and up. It could be anticipated that at such power levels the pumping system is integrated with a small electric grid, supplying electricity for other purposes than water pumping alone.

2.7.1 Rural Water Supply

Water supply demand for livestock and domestic purposes is more or less constant throughout the year. Typical water demands in rural areas in a country like Ethiopia can be estimated to be 20lit per day per person. Reasonable costs of pumping water run up to US $ 1 per m^3, especially in very arid zones, in exceptional cases costs can be even higher. In rural water supply systems storage tanks are normally included, even for engine-driven pumps (because of the risk of breakdowns or lack of fuel), but not for hand pumps. [1]

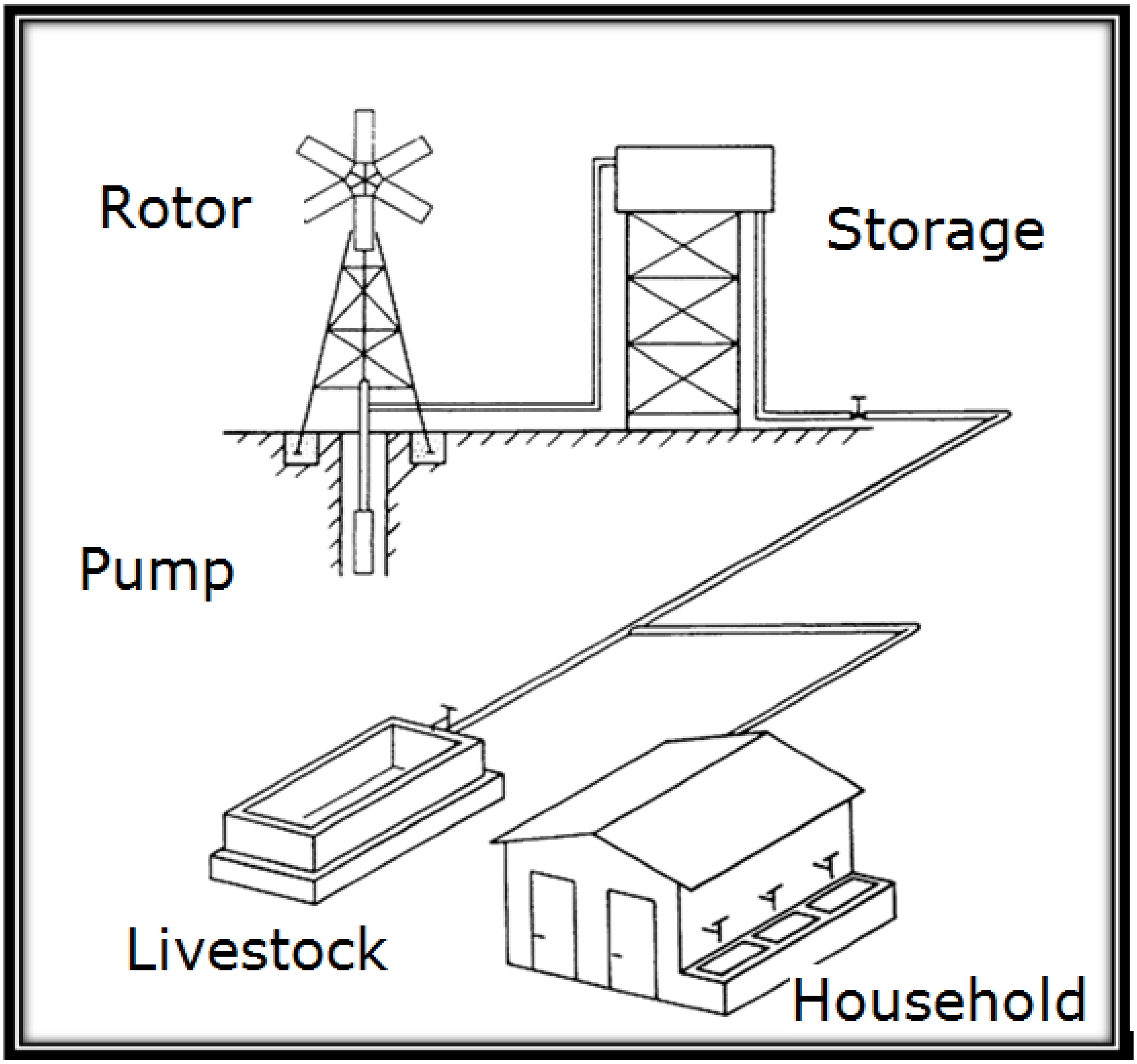


Figure 2-10: Schematic layout of a village water supply system showing the five major components.

2.7.2 Irrigation

Demand of water for irrigation is seasonal. Average demand in a peak month can be 2-5 times higher than the average demand over a year. Water for irrigation is used normally during the dry season where the availability of rain is low. In general unit water costs for irrigation should be well below \$ 0.10/m^3. This implies that pumping water by any pumping device from great depths; say more than 30 m is normally not economically viable. If wind pumps are used for irrigation, normally a storage tank must be included in the system. [1]

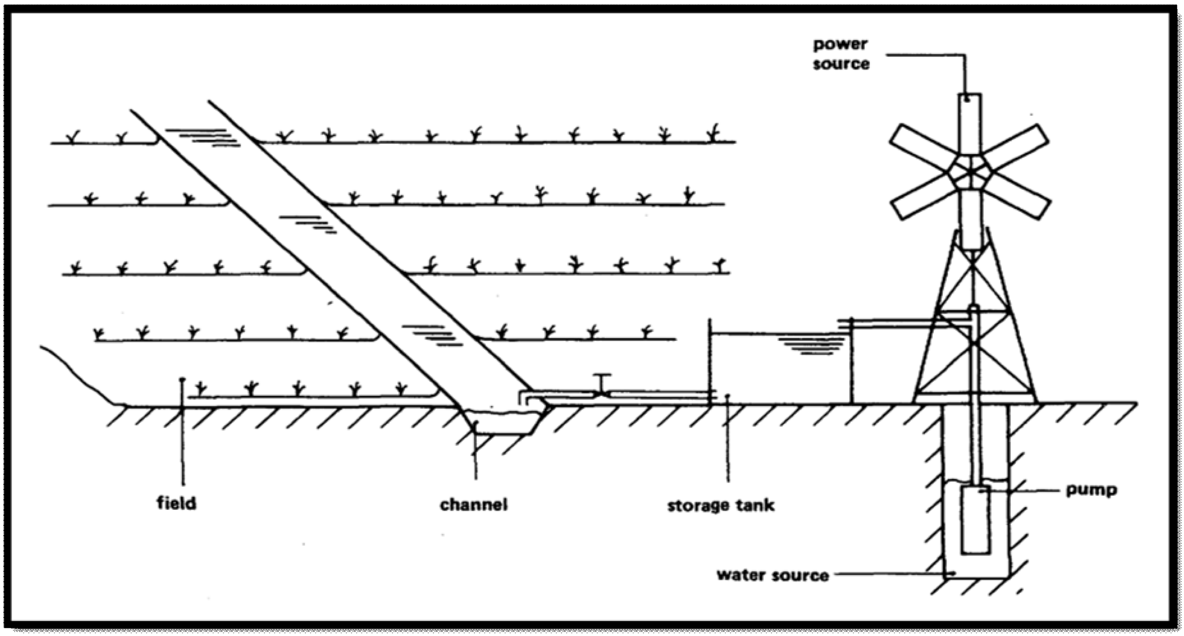


Figure 2-11: Schematic layout of a small scale irrigation system showing the six major components.

2.8 Components of Mechanical Wind Pump

A mechanical windmill working on water pumping consists typically of the following components:

- **Rotor,** which captures the wind's energy and converts it into mechanical energy.
- **Transmission**, which conveys the energy from the rotor to the pump, sometimes involving intermediate energy conversions.
- **Pump**, which push the water to storage tank
- **Safety system**, which protects the windmill during gusts and storms.
- **Tower,** which supports the rotor and transmission system.

2.8.1 Rotor

The rotor is the essential part of this prime mover; it converts the power of the wind into useful mechanical shaft power. Usually the blades consist of curved steel plates. Sometimes sails are used. Classical "American" windmills have 15, 18, 24 or even 36 blades, mostly supported by a structure of spokes and rims. These rotors deliver maximum power when the speed of the blade tips approximately equals the wind speed. Recent designs have fewer blades: 4, 6, 8, or 12, mostly supported by spokes only. These rotors operate at higher tip speeds: For any given wind speed, maximum power is delivered when the speed of the blade tips equals 1.5 to 2 times the wind speed.

The rotor is fixed to a steel shaft by means of one or two hub plates. The shaft is supported by sleeve bearings (receiving oil from the gear oil bath), or by roller bearings (lubricated by grease or by oil), or by hardwood sleeve bearings (lubricated with oil). Rotors of water pumping windmills range from 1.5 to 8 m diameter.

2.8.2 Transmission

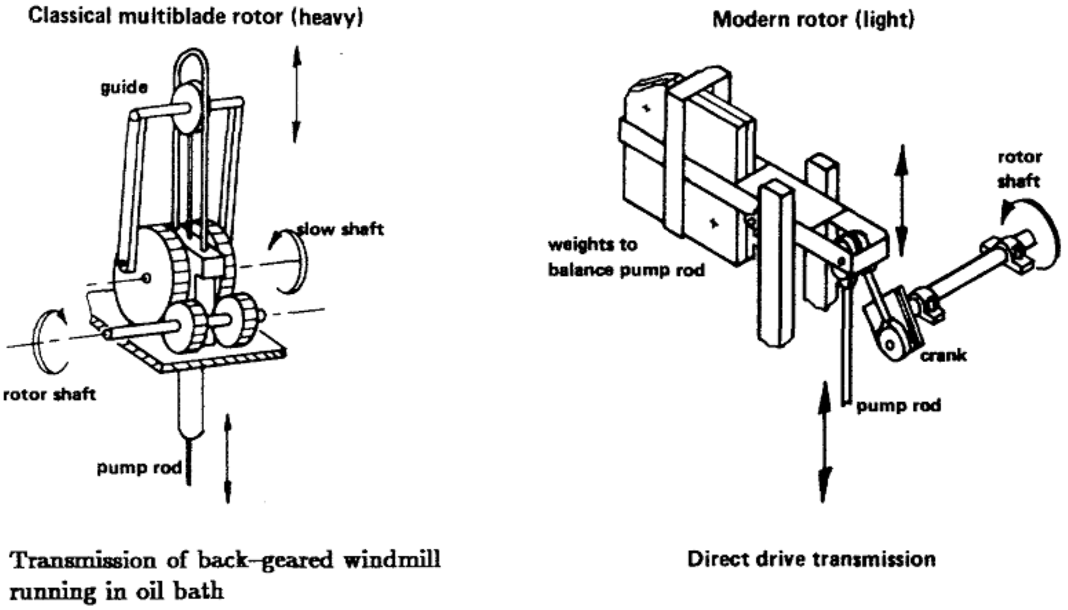
The transmission of a windmill conveys the mechanical energy delivered by the rotor to the pump through pump rod. Many of the classical "American" windmills, especially the smaller models are "back-geared", i.e. they incorporate a gear box. The gears reduce the rpm. of the pump, normally by a factor of about 3. The gears are normally double to avoid uneven loading of the crank mechanism and usually run in an oil bath for lubrication. The oil needs to be changed about once a year.

An essential part of a windmill transmission is some kind of eccentric that transforms the rotating movement of the rotor into a reciprocating movement of the pump rod. Several types exist:

- Two drive rods connected eccentrically to the two slow gears, and connected through a guide to the pump rod (see Figure 2.12 below).

- A simple crank on the main shaft, connected directly to the pump rod.
- A crank on the main shaft, connected through a guide to the pump rod.
- A crank on the main shaft, connected through a lever system to the pump rod.

The pump rod transmits the power to the pump. Often a swivel joint is incorporated, preventing the pump rod from rotating when the windmill's head assembly is yawing due to a change of wind direction. Normally the pump rod is guided at several points in the tower. The swivel joint and the guides require regular lubrication by greasing, for example once a month. The efficiency of the transmission is somewhere between 70% and 90%.


Classical multiblade rotor (heavy)

Modern rotor (light)

Transmission of back–geared windmill running in oil bath

Direct drive transmission

Figure 2-12: Back-geared and direct driven transmission systems [1]

2.8.3 Safety System

No wind machine can be expected to survive very long without an automatic safety system to protect it against gusts and storms. It would be impractical, even if it were possible, to design a wind machine strong enough to remain in full operation during storms, with an exception perhaps for very small wind machines of 1 m diameter or so. Hand-operated safety systems alone are not sufficiently reliable. Storms may occur very suddenly, unexpected storms may occur at night, and one moment of negligence may reduce an important investment to scrap.

The safety system of mechanical windmills is combined with the orientation system. At low wind speeds the rotor is oriented into the wind; with increasing wind speeds the rotor is gradually turned out of the wind so as to limit the speed of the pump and the forces acting on the structure.

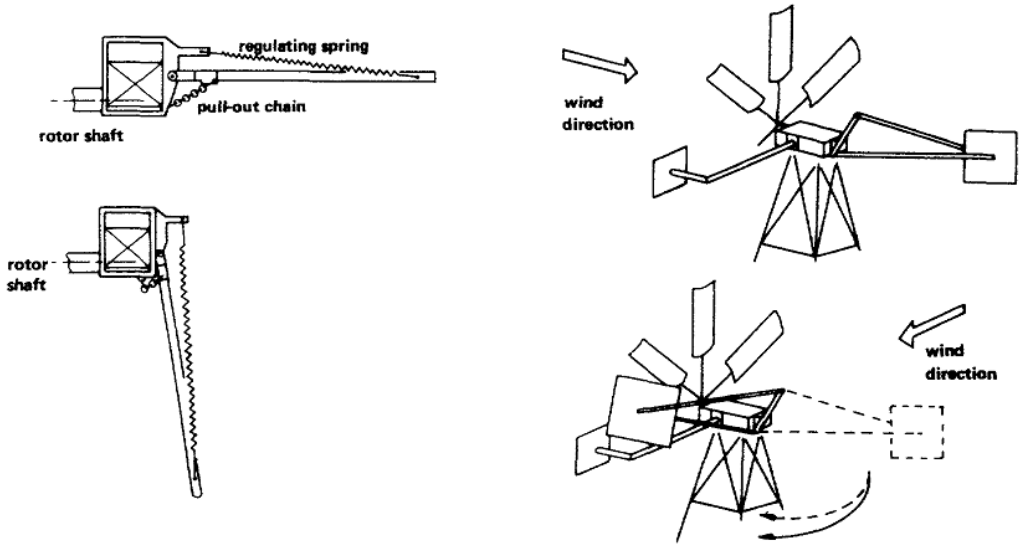
The functioning of these safety systems is based on the equilibrium of aerodynamic forces (acting on one or two vanes and the rotor), and some other force (mostly a spring or weight) that serves to counteract the aerodynamic forces. Normally the automatic safety system can also be operated manually to stop the windmill.

A mechanical brake is sometimes incorporated in the rotor hub. It is normally operated both by the automatic safety system and by the manual furling mechanism. These brakes are not capable of stopping a windmill in a storm. They merely hold the windmill when it is being serviced or when there is no need of water.

Two important characteristics of a safety system are:

- The rated wind speed V_r, at which the windmill reaches its maximum rotational speed, and hence pumping rate. For higher wind speeds the rotational speed is limited and gradually reduced by the automatic safety system. V_r is normally 6 to8 m/s.

- The cut-out wind speed V_{out}. At this wind speed the rotor is completely turned out of the wind and stops running. Usual values are 15 to 20 m/s.



Top view of ecliptic safety system

Hinged vane safety system

Figure 2-13: Typical mechanical safety system

2.8.4 Tower

The three components discussed above (rotor, transmission, and safety system) together form the head assembly of the windmill. It is supported by a tower, which raises the assembly over any obstructions into a fair, unobstructed wind. In addition the tower serves as a rig when installing the pipes of deep well pumps. Windmill towers are normally of lattice construction, factory welded as complete sections, or bolted together at the installation site. Normally they have four legs, sometimes three. Tower heights range from 6 m for small windmills to 18 m for large windmills. The most common height is around 10 m.

2.8.5 Pump

The majority of water pumping windmills are equipped with single-acting piston pumps. As shown in the Figure 2-14 below. When the piston moves down, the foot valve closes and water passes through the open piston valve. On the upward stroke the valve in the piston closes, the foot valve opens, and water is pumped.

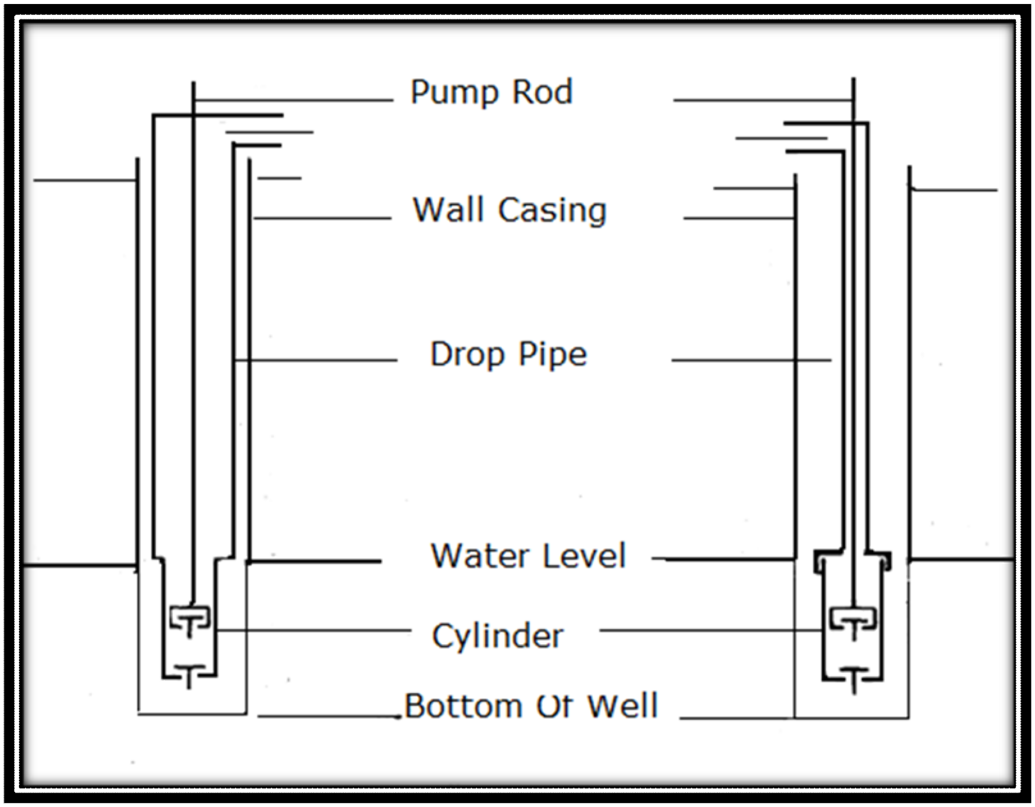


Figure 2-14: Deep well pump arrangement[1]

A variety of materials are used for the cylinder: brass, stainless steel or PVC pipe but also a bronze bushing inside a cast iron cylinder. The sealing between piston and cylinder wall is normally realized by means of a leather cup. In high-pressure pumps (for large pumping heads) one finds two or sometimes three cups above each other. The leather cups are subject to wear and usually replaced after six months to two years, depending on the quality of the water. The piston body and valves are mostly made of brass (cast and/or machined). Valves are normally lined with some type of rubber for better sealing. If the delivery head is higher than the point where the pump rod leaves the delivery pipe, a pump rod sealing is required.

2.9 Storage and Distribution

An important part of pumping systems is the storage and distribution of water. The efficiency of storage and distribution (i.e. the proportion of pumped water which actually reaches its point of use) has its effect on the size of the pumping system. High efficiency storage and distribution allow smaller pumping systems to be used. The static head of the storage tank and the pressure losses in the distribution system determine the pressure for which the pump must be designed.

2.9.1 Storage for Rural Water Supply

In water supply systems for human consumption, storage tanks are usually used, even in combination with engine-driven pumps. In the case of engine-driven pumps, the tank stores the water which is pumped in a short period at a high flow rate for use over a longer period. It pressurizes the distribution system and forms an emergency stock of water. For a wind pump, normally a larger storage capacity is needed to cover 1 to 2 days of demand. Usually some head is needed in the distribution system; therefore overhead tanks are used, or tanks of a cheaper construction at a sufficiently high point in the landscape. Tanks storing water for human consumption should always be covered to minimize pollution by dirt, insects and animals and to prevent algae growth (by shading the water from the sunlight).

2.9.2 Storage for Irrigation

In irrigation schemes, based on engine-driven pumps, no water storage tanks are used. The water is pumped directly into the irrigation system, be it canals or pipes. The main function of a storage tank in windmill irrigation is water management control. It stores the water which is pumped during periods when it is not immediately used, especially during the night. It allows the farmer to irrigate during short periods at a high, constant flow rate.

When using a wind pump for irrigation, it is essential to minimize the cost of the tank, since the cost of the water would otherwise become too high to justify its use for irrigation. Capacities of 1/2 day to 2 days are usual. Cheap earth bund tanks are preferred. Overhead storage tanks are prohibitively expensive for this application; hence irrigation systems requiring a high pressure (such as sprinklers) are normally not feasible.

2.10 Viability of wind pumping

It is important to consider previous technical and economical work experiences and recommendations to make the pre-feasibility of wind pumping in comparison to different pumping methods. Table 3.1 gives a rough indication of the comparative cost effectiveness of different pumping methods against three measuring parameters. It may help to eliminate certain options at a first glance and show which options merit further study.

Table 2.1: Comparative cost effectiveness for different pumping methods [1].

Average wind speed in critical month(m/s)	Average daily hydraulic demand in critical month					
	20-500m4/day		50-2000m4/day		2000-100,000m4/day	
	Rural water supply	Irrigation	Rural water supply	Irrigation	Rural water supply	Irrigation
>5	Wind best option	Wind best option	Wind best option	Wind best option	Wind best option	Wind best option
3.5-5	Wind best option	Wind probably best option but check with Diesel	Wind best option	Wind probably best option but check with kerosene and Diesel	Wind very good option but check with Diesel	Wind very good option but check with Diesel
2.5-3.5	Consider all options wind, solar, kerosene ,Diesel	Consider all options wind ,solar, kerosene ,Diesel	Consider wind, kerosene, Diesel	Consider wind, kerosene, Diesel	Consider wind and Diesel	Consider wind and diesel
2.0-2.5	Consider, Solar ,kerosene ,Diesel, check wind	Consider solar, kerosene, Diesel, wind doubtful	Consider kerosene, Diesel, check wind	Consider kerosene, Diesel, wind doubtful	Diesel best option, wind doubtful	Diesel best option, wind doubtful
<2.0	Consider, Solar, kerosene, Diesel	Consider, solar, kerosene, Diesel	Consider kerosene, Diesel	Consider kerosene, Diesel	Diesel best option	Diesel best option

The data that should be available to carry out the pre-feasibility study are:

1. **Average daily hydraulic energy requirements** for each month of the year, expressed in m4 per day.
2. **Average monthly wind speeds** over the year.
3. **The critical month -** that month in which the ratios of the daily hydraulic energy demand to the available wind potential of that month is largest. To determine the critical or "design" month, for each month divide the daily hydraulic energy demand by the cube of the average wind speed of the same month. The highest value determines the critical month. For rural water supply with a constant water demand the critical month is obviously that with the lowest average wind speed.

According to World Bank manual, below 20 m^4/day hand pumps are probably always the best solution. Very large requirements above 100,000 m^4/day are excluded in the table, since standalone wind pumps are not a very realistic alternative for this range. The reason for making a distinction between "rural water supply" and "irrigation" is that, the water requirements over the year for a rural water supply are more or less constant, implying that the wind pump is used all the year around. In contrast, the demand of water for irrigation is seasonal, so the wind pump will stand idle during part of the year. Considering the high capital investment involved, this puts the wind pump for irrigation at a high disadvantage over diesel/petrol.

Generally, based on practical experience World Bank manual recommends

- Average wind speed below 2 m/s in the critical month wind energy for water pumping is generally not economically feasible.
- Average wind speeds in the critical month above 3.5 m/s, wind pumps are generally a very good option.
- At average wind speeds in the critical month between 2 and 3.5 m/s it is impossible to make general statements on the economic viability of using wind energy for water pumping. In this case it needs detail technical and economic analysis.

- Wind pumps are particularly attractive at low hydraulic power requirements (low head and/or low water requirement). At very low requirements (< 20 m^4), however, it is better to use hand pumps.

2.11 Diesel Water Pumping System

When considering the use of a wind pump, it is good practice to consider alternative pumping systems also. In this regard, Diesel pumping system will be alternative water pumping system in consideration for this paper. A Diesel pump typically consists of four main components:

Diesel engine**:** This is the main component of Diesel pumping and prime mover for the pump. The engine is direct-coupled to the discharge head/pump head using twisted V-belt.

Pump element**:** The most common pump type is the helical rotor pump also referred to as the progressive cavity pump and the piston pump. Positive displacement pumps are fully convertible to electric motor drive when power becomes available from the grid. In addition it has less operational components than submersible pumps.

Discharge/Pump head**:** The discharge head is fitted above the centre of the borehole. The rising main is fitted to the bottom of the discharge head and the engine is coupled to the pulley through belts. The discharge head transfers the power of the engine to the pump via a circular (progressive cavity) or a reciprocating (piston) action.

Rising main**:** The rising main usually consists of 3m galvanized steel pipes (40 or 50 mm diameter) which are coupled together. The rising main pipes either come with a taper thread or parallel thread. The taper is cheaper to manufacture but does not exhibit the strength of the parallel threaded pipe. Taper threaded pipes are recommended for hand pumps but not Diesel pumps. However in reality, taper threaded pipes are often installed due to the initial cost savings. A shaft transfers the power down the centre of the column either through a circular action or through a reciprocating action. The shaft is guided either through bobbin bearings or guides.

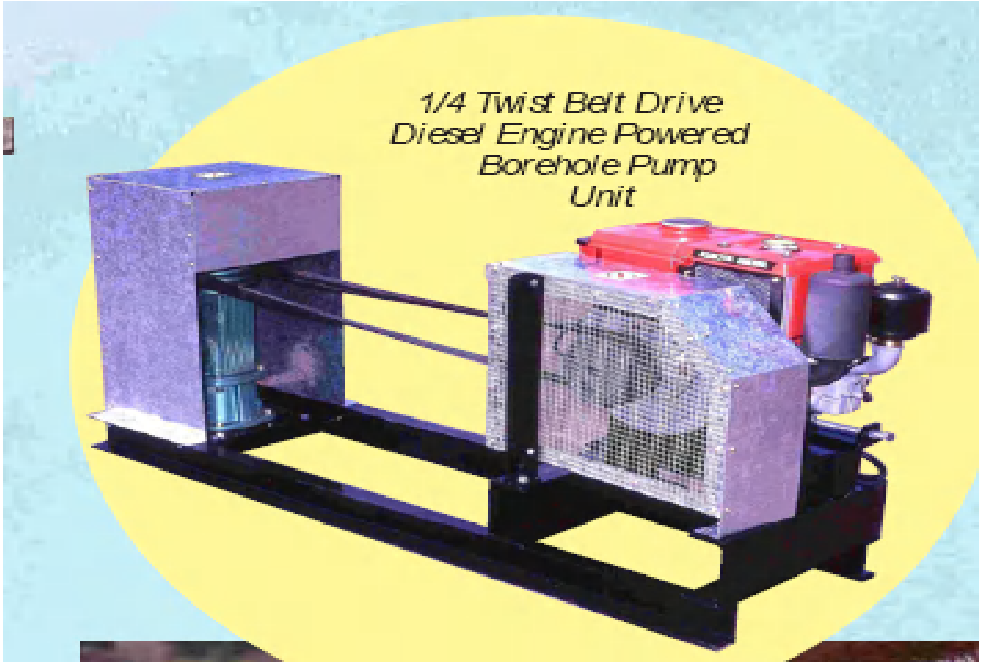


Figure 2-15: Diesel engine driven borehole progressive cavity pump

CHAPTER 3

3. Wind Potential Assessment

3.1 Statistical Models for Wind Data Analysis

The wind speed probability density distributions and their functional forms represent the major aspects in wind related literature. They have a wide range of applications, including identifying the parameters of the distribution functions and analyzing the wind speed data as well as wind energy economics. Various probability functions have been tested many times with the field data to identify suitable statistical distributions for representing wind regimes. It is found that two of the commonly used functions Weibull and Rayleigh distributions for fitting a measured wind speed probability distribution in a given location over a certain period of time describe the wind variations in a regime with an acceptable accuracy level.

3.1.1 Weibull Distribution

In Weibull distribution, the variations in wind velocity are characterized by the two functions: (1) the probability density function and (2) the cumulative distribution function. The reliability of Weibull distribution in wind regime analysis depends on the accuracy in estimating Weibull parameters.

The probability density function of the Weibull distribution is given by

$$f(V) = \left(\frac{k}{c}\right)\left(\frac{V}{c}\right)^{k-1} \exp\left[-\left(\frac{V}{c}\right)\right]^{k} \qquad 2.6$$

Here, f (V) is the probability of observing wind speed V; c is the Weibull scaling parameter and k is the dimensionless Weibull shape parameter.

The corresponding cumulative probability function of the Weibull distribution is given by

$$F(V) = 1 - \exp\left[-(\frac{V}{c})\right]^k \qquad 2.7$$

3.1.2 Rayleigh Distribution

The reliability of Weibull distribution in wind regime analysis depends on the accuracy in estimating k and c. For the precise calculation of k and c, adequate wind data, collected over shorter time intervals are essential. In many cases, such information may not be readily available. The existing data may be in the form of the mean wind velocity over a given time period. Under such situations, a simplified case of the Weibull model can be derived.

The Rayleigh distribution is a special case of the Weibull distribution in which the shape parameter k takes the value 2.0. From equation 2.6 the probability density function for the Rayleigh distribution can be simplified as

$$f(V) = (\frac{2V}{c^2})\exp\left[-(\frac{V}{c})\right]^k \qquad 2.8$$

The mean value and standard deviation can be computed from

$V_m = \int_0^\infty Vf(V)dV$, substituting eq(2.8) and manipulating the result

$V_m = c\int_0^\infty e^{-x}x^{1/k}dx$, and comparing with the standard Gamma function $\Gamma n = \int_0^\infty e^{-x}x^{n-1}dx$

The average velocity can be expressed as

$$V_m = c\Gamma\left(1+\frac{1}{k}\right) \qquad 2.9$$

The standard deviation can be formulated from the relation,

$$\sigma_V = (\mu_2' - V_m{}^2)^{1/2}$$

Where μ_2' is the second raw moment of population which is given by ,

$$\mu_2' = \int_0^\infty V^2 f(V)dV$$

Substituting for f (V) and manipulating with gamma function, we have a standard deviation expressed as weibul parameters as;

$$\sigma = c\left[\Gamma\left(1+\frac{2}{k}\right) - \Gamma^2\left(1+\frac{1}{k}\right)\right]^{1/2} \qquad 2.10$$

Where: **Γ** is the gamma function.

Introducing mean wind speed in to eq (2.10), we have a more condensed equation as,

$$\left(\frac{\sigma}{v_m}\right)^2 = \frac{\Gamma(1+\frac{2}{k})}{\Gamma^2(1+\frac{1}{k})} - 1 \qquad 2.11$$

Hence the Weibull factors k and c can be estimated from the mean and standard deviation of wind data by solving the above expression numerically.

In a simpler approach an acceptable approach [Manwell, 2002] is given by:

$$k = \left(\frac{\sigma}{V_m}\right)^{-1.086} \qquad 2.12$$

3.2 Hourly Wind Speed Generation

In all Ethiopian metrological stations, where wind measurement is available reading is taken five times a day to the maximum during the day time(6:00,9:00,12:00,15:00 and 18:00). And in most of stations the reading is not complete. In this work wind data from 35 stations with three consecutive year's duration are analyzed. Since the measured data are only day time data, it is required to know the night time distribution from the day time data. In recent wind potential assessment work done by [5] on four typical places in Ethiopia, different assumptions and methods to fill the night time data gap are discussed. These assumptions are:

1. The first assumption is to use only data from the daytime recorded between 6:00 and 18:00 at intervals of 3 h, representing 15h instead of 24hr.
2. The second assumption is to replace the missing nighttime data with the minimum wind speed recorded during the day.
3. The third is to consider the average daily wind speed to be the nighttime wind speed from 19.30 to 4.30.
4. The fourth assumption is to use the averages of the morning 6:00 and the evening 18:00 readings for the missing nighttime data.
5. The final assumption is to distribute the daytime data over a 24 h period, stretching the time interval from 3 h to approximately 5 h. This is equivalent to assuming that the average daily wind speed is the same as the average for 24 h.

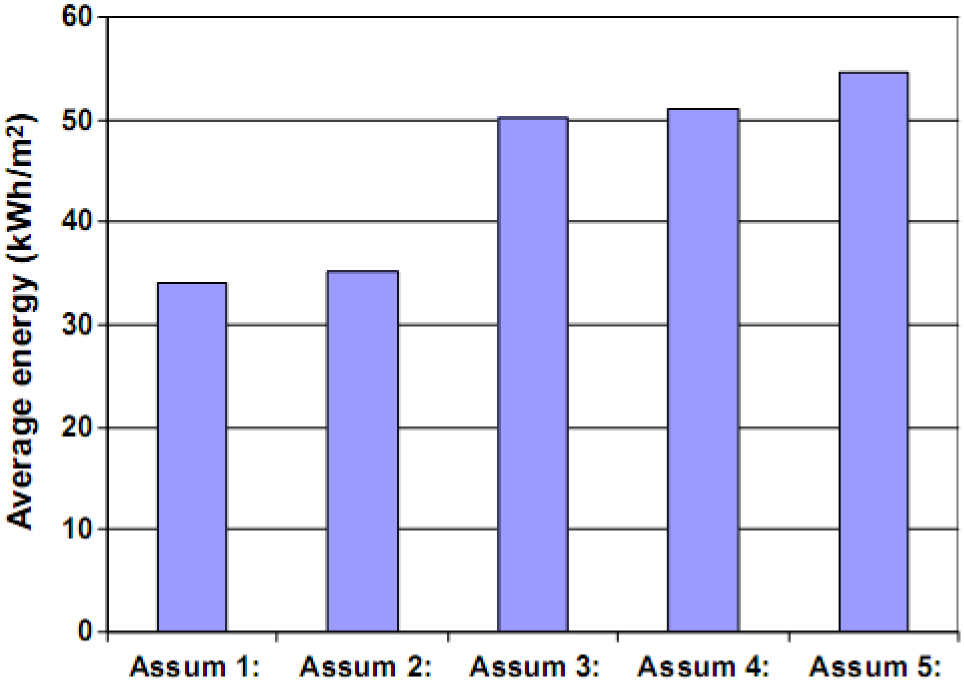
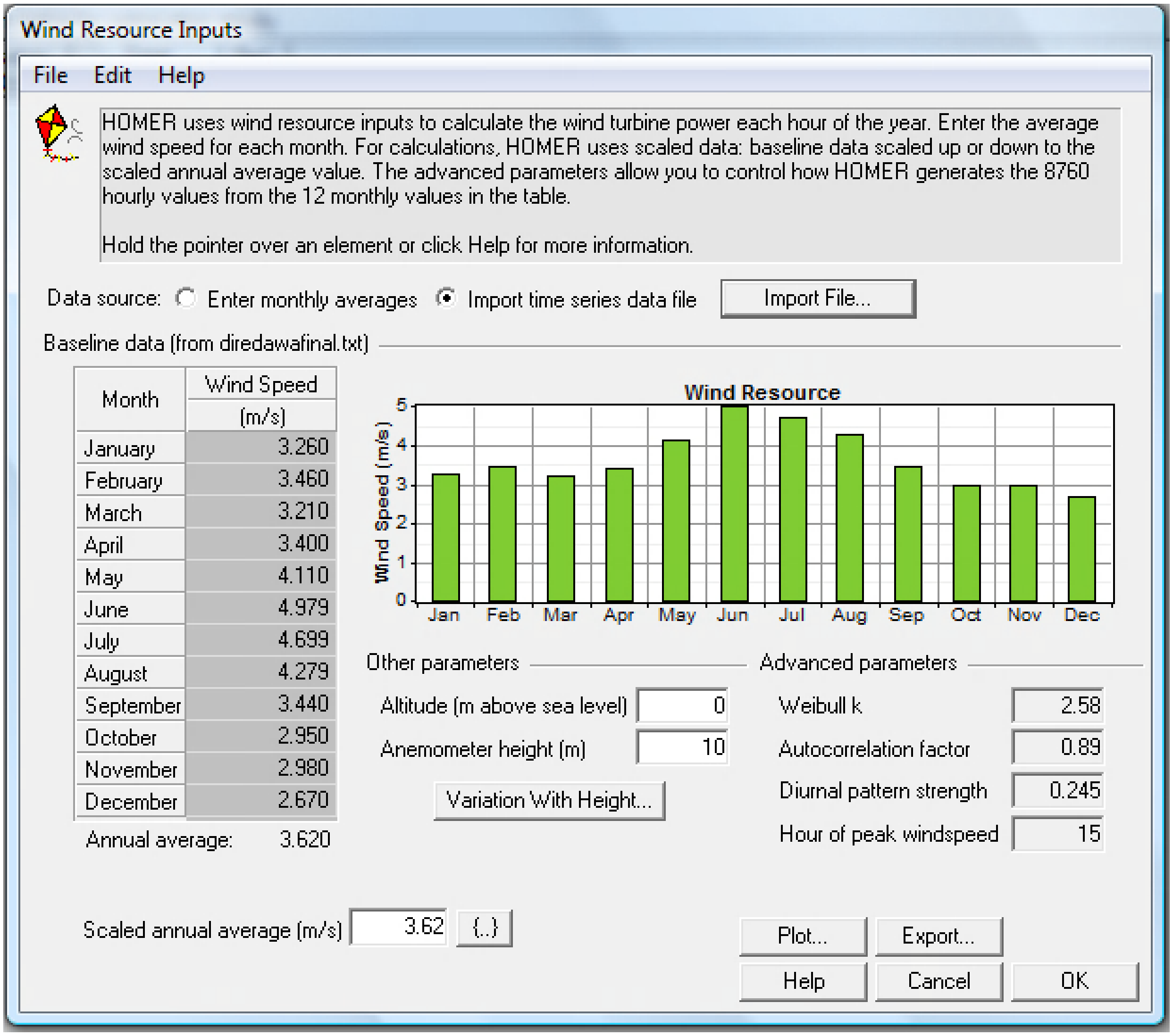


Figure 3-1: Addis Ababa energy histogram for January 2001–2003 under different assumptions [G.Bekele, Björn Palm, 2008]

So, based on the different assumptions the total energy over the period is shown in the histogram. From the result one can conclude that considering night time wind has considerable energy. This is achieved better in assumption five where the day time data at 3hour interval is stretched to approximately 5hour over the day. In addition to this [G.Bekele, Björn Palm, 2008] use a Hybrid Optimization Model for Electric Renewable (HOMER) software to synthesize hourly data to fill the night time data.

In this work, Assum 5 is practiced with the help of Hybrid Optimization Model for Electric Renewable (HOMER) software to fill the night time wind. The software is a micro-power optimization model for both off-grid and grid-connected power systems in a variety of applications and used here only for generation of year round hourly wind speed using some advanced input parameters. The Weibull shape parameter which is an indication of the breadth of the distribution of wind speeds is calculated using the simplified equation 2.12.



HOMER uses wind resource inputs to calculate the wind turbine power each hour of the year. Enter the average wind speed for each month. For calculations, HOMER uses scaled data: baseline data scaled up or down to the scaled annual average value. The advanced parameters allow you to control how HOMER generates the 8760 hourly values from the 12 monthly values in the table.

Hold the pointer over an element or click Help for more information.

Data source: ○ Enter monthly averages ● Import time series data file

Baseline data (from diredawafinal.txt)

Month	Wind Speed (m/s)
January	3.260
February	3.460
March	3.210
April	3.400
May	4.110
June	4.979
July	4.699
August	4.279
September	3.440
October	2.950
November	2.980
December	2.670
Annual average:	3.620

Other parameters

Altitude (m above sea level) 0

Anemometer height (m) 10

Advanced parameters

Weibull k 2.58

Autocorrelation factor 0.89

Diurnal pattern strength 0.245

Hour of peak windspeed 15

Scaled annual average (m/s) 3.62

Figure 3-2: HOMER users interface [HOMER].

The other input parameters are diurnal pattern strength, autocorrelation factor and hour of pick wind speed. Typical values for diurnal pattern strength range from 0 to 0.4 [HOMER], average value within the range 0.25 has been used. The autocorrelation function is a measure of the tendency of what a wind speed is likely to be, given what it was earlier [HOMER]. For complex topography the autocorrelation factor is (0.70 - 0.80) while for a uniform topography the range is higher, (0.90 - 0.97). A typical range for the autocorrelation factor is 0.8 – 0.95 [HOMER]. For the selected sites an average value of 0.85 has been used here because the selected areas are somewhat averagely uniform topography. Hour of peak wind speed is the time of day that wind speed reaches maximum on average throughout the year. Based on the measured data's from NMSA, on average it takes 15GMT.Typical value is 14:00-16:00[HOMER].

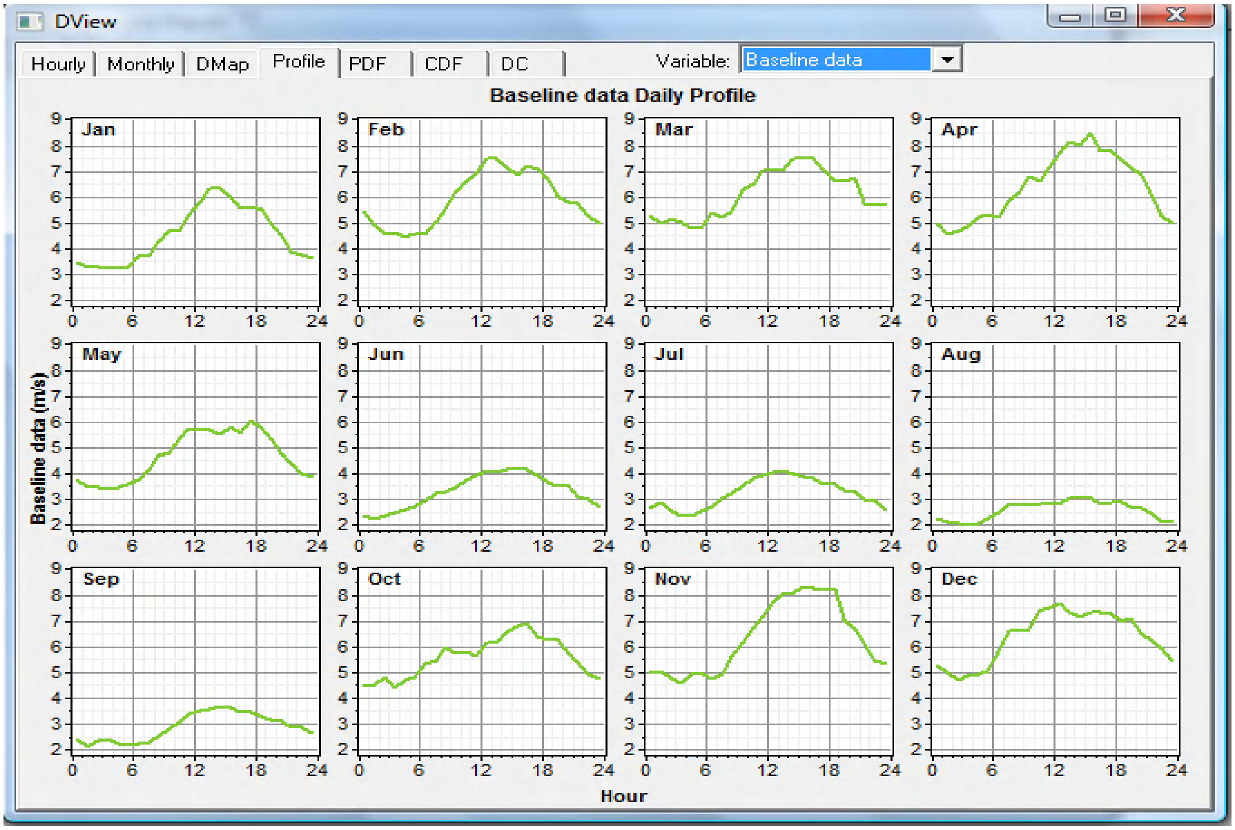


Figure 3-3: Predicted monthly wind speed profile [HOMER].

HOMER in the result window display, monthly wind speed, probability density function (PDF), cumulative density function (CDF) and the wind speed duration curve (DC).

Considering assumption five, it is assumed the available wind data as a complete data recorded over 24 hours daily (stretching from 3hr interval in to 5hr) and then the monthly average is calculated. This average is fed into the software along four advanced parameters and year round hourly wind speed is synthesized stochastically (8760hr).

Then from the synthesized data those particular data synthesized at that particular times during which the measured data was recorded (6:00, 9:00, 12:00, 15:00, and 18:00) and then their monthly average was calculated.

The monthly average is fed again to the software so that it synthesizes another set of hourly data. This time as expected, each synthesized hourly speed increases by a certain percentage. This is due to the reason that the daytime wind speed is higher than the night time.

To achieve the most probable night time wind in the regime, the second synthesized data is scaled down by appropriate factor to coincide with the first synthesized data, within a certain allowable mean arithmetic error.

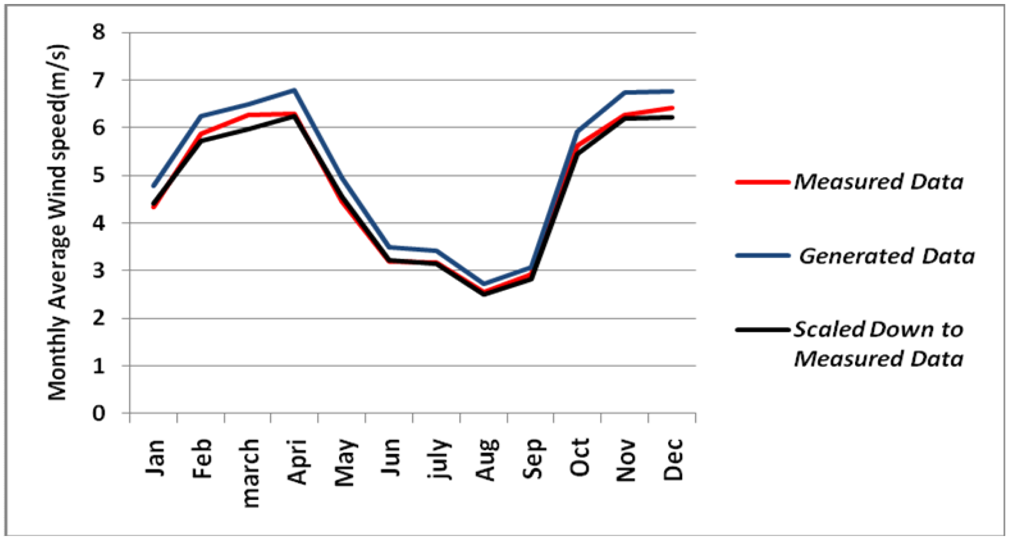


Figure 3-4: Hourly wind speed generation for Mekele

Considering Assumption five year round hourly wind speed is generated using HOMER for Aruba Island.As shown in Appendix C, Actual measured Diurnal average wind speed profile is compared to the generated Diurnal average wind speed profile. It shows monthly mean deviation ranges 4% (March) to 12% (April) and annual mean deviation 6.7%,which is very reasonable to fill missing night time data using Assumption five.

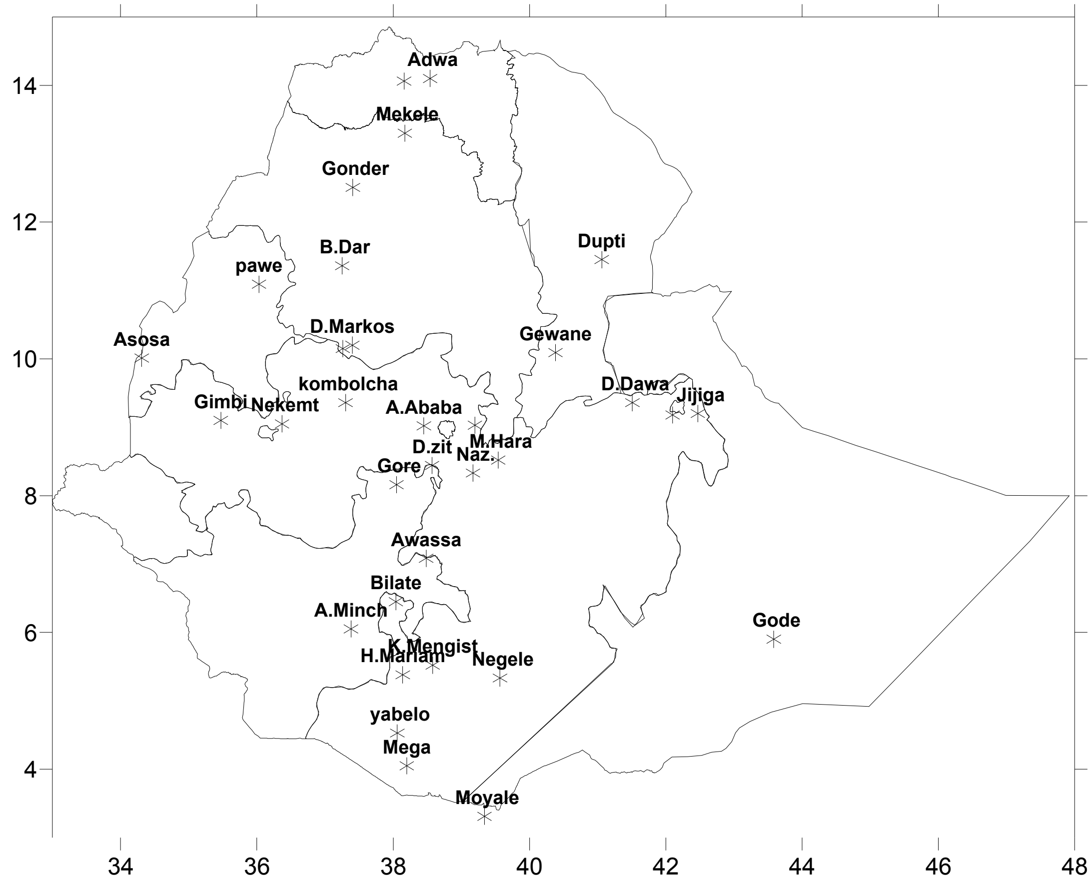


Figure 3-5: Stations in consideration available with a hourly wind speed five times a day

Most of the stations indicated on the map have hourly wind speed data recorded five times a day to the maximum and three times a day to the minimum. The density of data points is not sufficient to predict the wind distribution pattern on monthly and annual basis accurately, but it gives a rough indication how it looks like. This is mainly due to unavailability of wind data in the required form and limited number of wind speed measuring stations.

Table 3-1: Annual mean wind speed, Weibull shape and scale parameters

No.	Station	Shape parameter(k)	Scale parameter(C)	Observed mean speed(v_m) @10m	Observation year(GC)
1	Addis Ababa	2.85	5.68	4.7	2003-2005
2	Arbaminch	1.6	1.8	1.60	2003-2005
3	Awassa	1.7	1.75	1.56	2003-2005
4	Bahir dar	1.06	2.59	2.53	2003-2005
5	Dire Dawa	2.58	4.08	3.62	1999-2001
6	Gode	1.97	4.39	3.88	1995-1997
7	Gore	2.69	1.66	1.48	2003-2005
8	Gonder	1.17	1.25	1.18	1998-2001
9	Kombolcha	1.52	2.62	2.36	2000-2002
10	Mekele	1.78	5.4	4.79	2003-2005
11	Metehara	1.56	2.34	2.1	2003-2005
12	Negele	2.63	4.57	4.06	2003-2005
13	Nekemt	1.83	2.11	1.87	1996-1998
14	Moyale	4.48	5.18	4.71	2001-2003
15	Nazareth	3.04	4.78	4.25	1999-2001
16	Yabelo	2.48	3.28	2.91	2002-2004
17	Adwa	1.52	2.54	2.29	2001-2003
18	Jijiga	2.55	3.99	3.53	2001-2003
19	Asosa	2.37	4.12	3.64	2001-2003
20	Aykel	3.52	4.65	4.18	2003-2004
21	Dupti	1.38	2.35	2.14	2002-2004
22	Endesilase	1.93	2.85	2.53	2001-2003
23	Gelmso	1.47	2.78	2.52	2003-2004
24	Gewane	2.76	3.16	2.81	2001-2002
25	Hagermariam	2.04	2.43	2.16	2002-2004
26	Kibremengist	1.03	1.08	1.07	2001-2003
27	Debremarkos	1.98	2.26	2.01	2000-2002
28	Mega	4.16	3.47	3.15	1999-2001
29	Pawe	1.29	1.35	1.25	2001-2003
30	Gimbi	2.40	2.22	1.97	2002-2003
31	Bilate	2.18	3.65	3.23	1999-2002
32	Harar	1.55	3.57	3.20	2003-2004
33	Sholagbya	2.56	3.22	2.86	2003-2005
34	Mehalemeda	3.36	5.15	4.61	2002-2004
35	Debrezit	1.37	2.95	2.68	2000-2002

3.3 Annual Mean Wind Speed Distribution

Following the assumptions and methodology, annual wind distribution pattern along weibull parameters for each station is generated using HOMER as seen in Table 1.1. Most of the results found are similar in characteristics with previous similar works done so far in wind potential assessment. Strong variable annual wind speed is found in most of the stations and comparatively few stations show low annual variability.

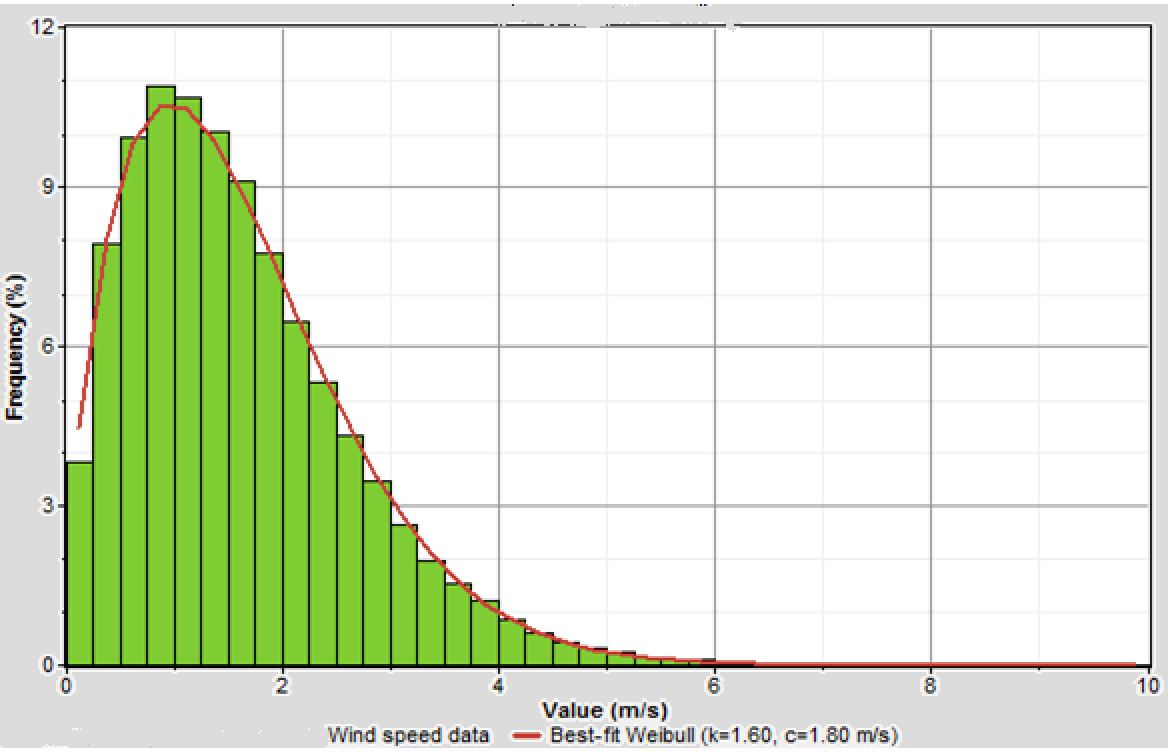


Figure 3.6: Arbaminch annual observed and Weibull distribution

Some of the stations which exhibit low monthly and annual wind speed along with moderate variability are Arbaminch, Awasa, Gore, Gonder, Nekemt and Kibremengist. Whereas Negele, Moyale, Mega, Nazareth, Aykel, Mekele and Addis Ababa Bole show strong monthly and annual wind speed, with low variability. In general for most of the stations moderate Weibull shape parameter is obtained, which ranges from1.6 to 2.56 for annual average greater than 2.5m/s.

This shows that the wind speeds are distributed over a wide range, advantageously this can be used for running wind turbines at its rated speed over a large portion of the time.

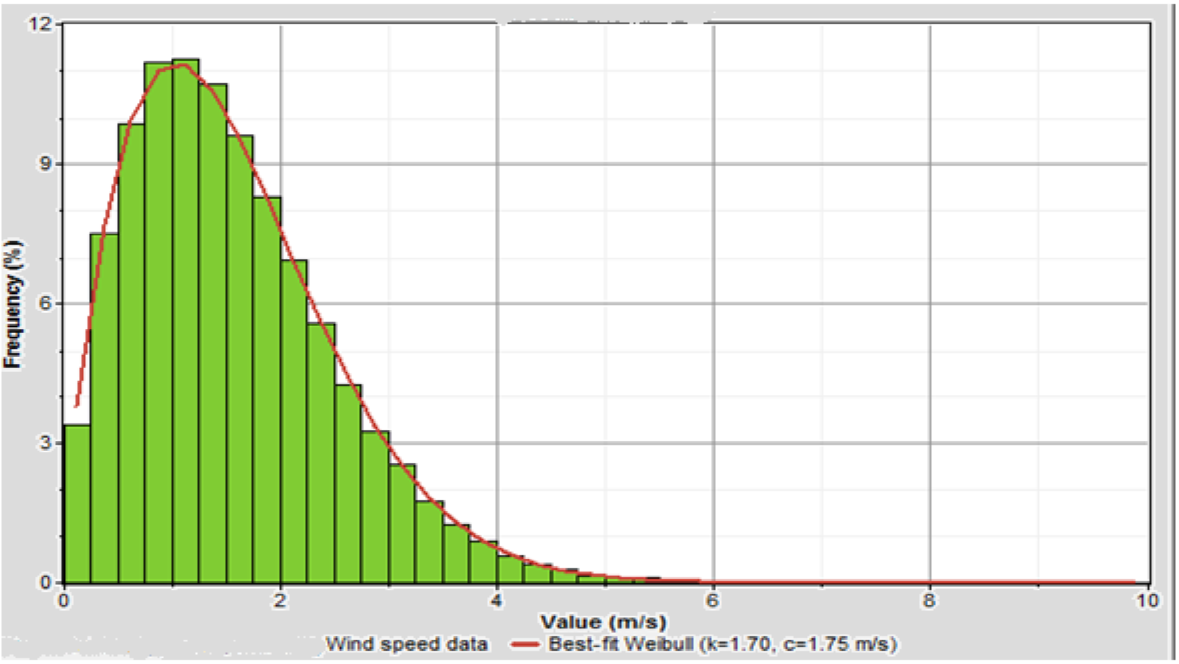


Figure 3-7: Awassa annual observed and Weibull distribution

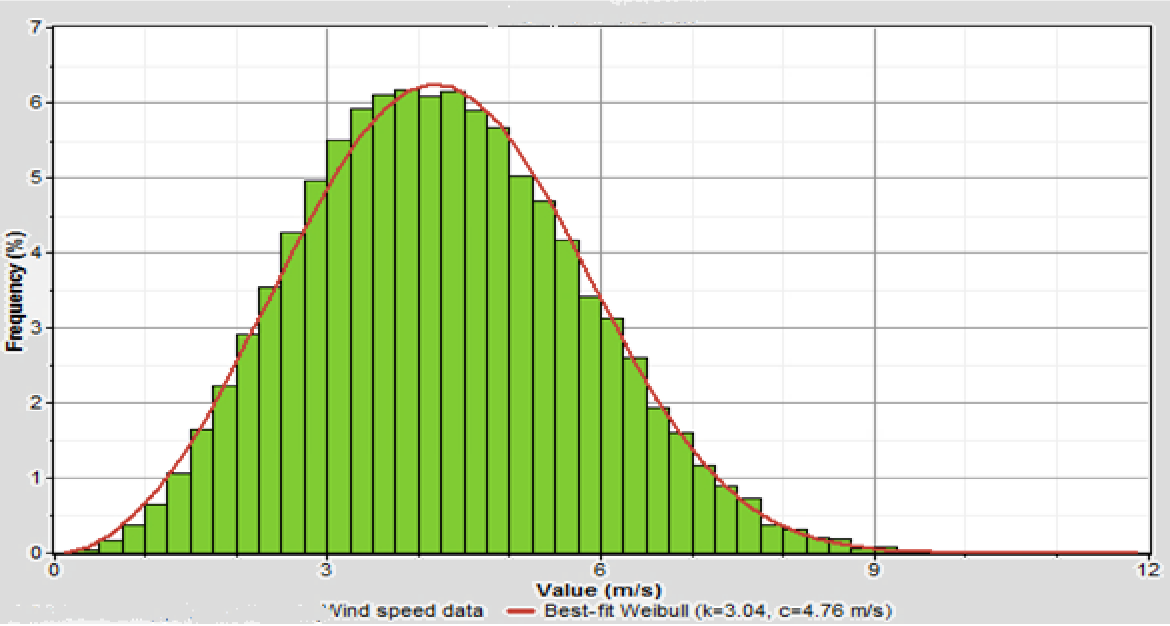


Figure 3-8: Nazreth annual observed and Weibull distribution

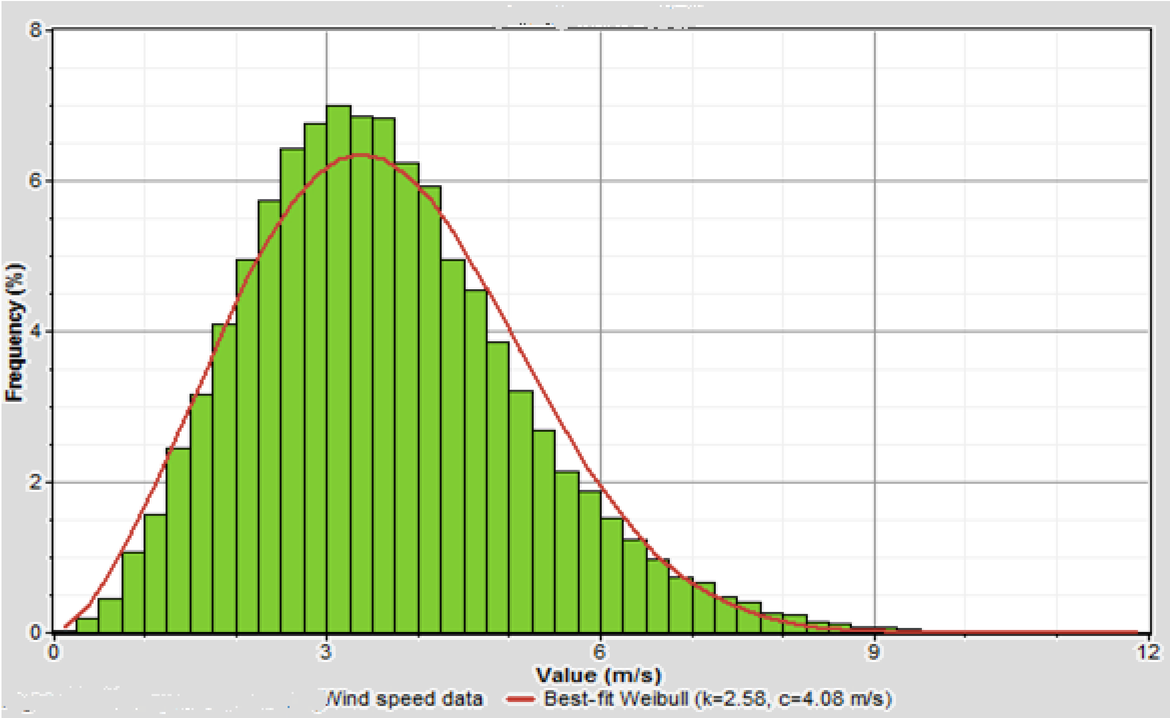


Figure 3.9: Dire dawa annual observed and Weibull distribution

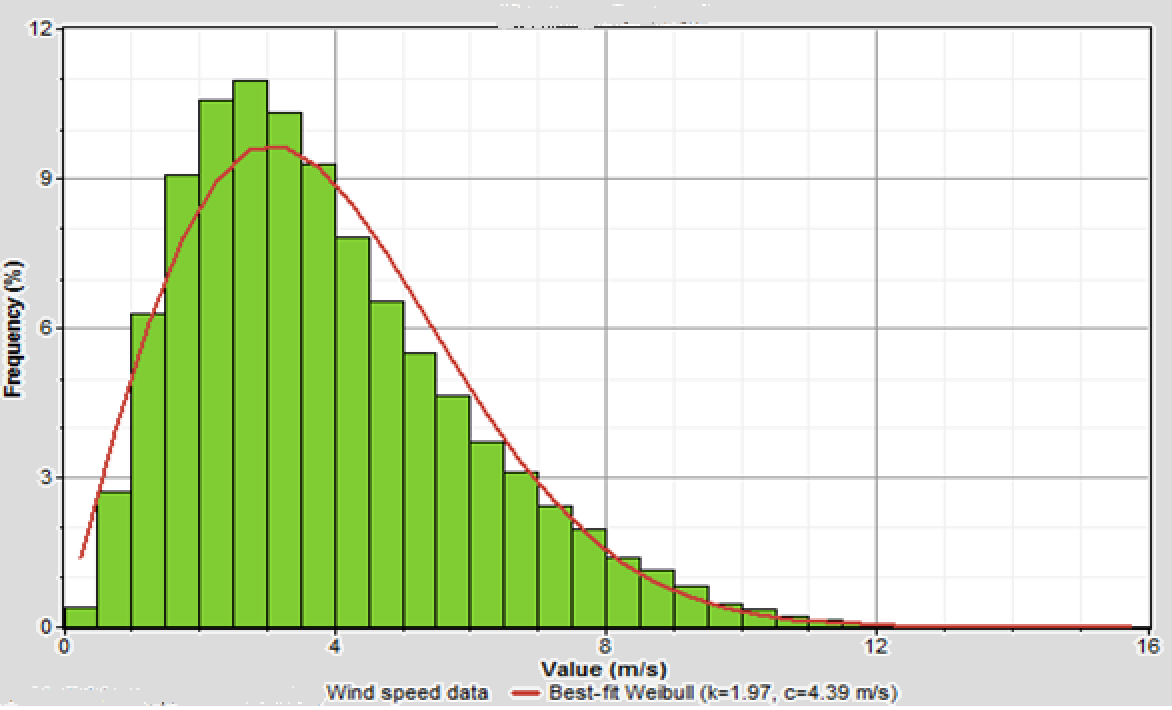


Figure 3-10: Gode annual observed and Weibull distribution

CHAPTER 4

4. Wind Pump Performance Analysis

4.1 Characteristics of Windmill

As for any prime mover, the most important characteristics of a windmill rotor are the torque-speed and power-speed curves. These curves depend on the wind speed and three important coefficients.

4.1.1 Tip Speed Ratio (λ)

When the blades are moving slowly, a portion of the air stream approaching the rotor may pass through it without interacting with the blades and thus without energy transfer. Similarly if the rotor is rotating fast and the wind velocity is low, the wind stream may be deflected from the turbine and the energy may be lost due to turbulence and vortex shedding. In both cases, the interaction between the rotor and the wind stream is not efficient and thus would result in poor power coefficient. Hence it is needed to incorporate a term tip speed ratio (λ) that controls these two far limits.

The tip speed ratio(λ) is the ratio between the speed of the blade tip and wind speed.

$$\lambda = \frac{\omega R}{V} \tag{4.1}$$

Where: ω is angular speed
V is wind speed
R is rotor radius

The design tip speed ratio λ_d is that value of λ for which the power coefficient reaches a maximum. The design tip speed ratio for classical "American" windmills is approximately 1 (slow-running). For more modern wind pumps it is somewhat higher: 1.5 to 2.0. [1]

4.1.2 Power Coefficient (C_P)

When the wind stream passes the turbine, a part of its kinetic energy is transferred to the rotor and the air leaving the turbine carries the rest away. Actual power produced by a rotor would thus be decided by the efficiency with which this energy transfer from wind to the rotor takes place. This efficiency is usually termed as the power coefficient (C_P). Thus, the power coefficient of the rotor can be defined as the ratio of actual power developed by the rotor to the theoretical power available in the wind.

$$C_P = \frac{P}{0.5\rho A V^3} \qquad 4.2$$

Where: P is rotor power out put
A is rotor area
ρ is density of air

The maximum power coefficient reached at λ_d, normally ranges from 0.3 to 0.4.[1]

4.1.3 Torque Coefficient (C_T)

It is the ratio of the torque delivered by the wind rotor, and a reference wind torque.

$$C_T = \frac{T}{0.5\rho A V^2 R} \qquad 4.3$$

Since power is equal to rotational speed times torque ($P = \omega T$), a similar relation is found for the corresponding coefficients: $Cp = \lambda C_T$. For water pumping windmills the starting torque coefficient C_T (λ=O) is of special interest. The following rule of thumb is often applied: $C_T(\lambda\text{=O}) = 0.5/\lambda_d^2$.[1]

4.1.4 Design Wind Speed (V_d)

It is defined as the wind speed for which the ratio of hydraulic power output to the available wind power is maximum. At this design wind speed the overall power coefficient is maximum; its value is one of the important parameters in describing the performance of a wind pump.[1]

4.1.5 Overall Power Coefficient ($C_p\eta$)

The overall power coefficient includes rotor power coefficient C_p, and the efficiency of the transmission and pump. It is the ratio of hydraulic power output to wind power input at a given wind speed, which is attained at the design wind speed V_d.

4.2 Mathematical Description of Wind Pump Out put

In order to simplify the mathematical description of the output of water pumping, assumptions which are practically reasonable are.

1. The average torque exerted by the pump is constant.

2. The C_T-λ characteristics of the wind rotor is linear, except at starting condition.

The first assumption implies that the torque produced by the rotor at speed V must be equal to the torque produced at V_d (design speed).

$C_T \frac{1}{2}\rho A V^2 R = C_{Td} \ \frac{1}{2}\rho A V_d{}^2 R$, which can be expressed as

$$\frac{C_T}{C_{Td}} = \frac{V_d{}^2}{V^2} \qquad 4.4$$

The second assumption can be written algebraically, as

$$C_Q = \frac{C_{Qd}}{\lambda - \lambda_d} * (\lambda_{\max} - \lambda) \qquad 4.5$$

Substituting Eq (4.4) in to Eq(4.5),yields

$$\frac{V_d^{\,2}}{V^2} = \frac{\lambda_{\max} - \lambda}{\lambda_{\max} - \lambda_d} \qquad 4.6$$

Where: $\lambda_{\max}$ is the maximum tip speed ratio of windmill.

4.3 Start and Stop Behavior of Water Pumping Windmill

A special problem of windmills driving piston pumps is starting,due to the finite weight of pump rods, in addition to the water column lift. To start a windmill, needs a high wind speed to overcome the peak of the pump torque. This wind speed is called V_{start} or cut-in speed. It is higher than the design wind speed V_d. Once the windmill is running, the rotor, thanks to its inertia, only "feels" the average torque demanded by the pump, but not the weight of the pump rod (the energy to lift the pump rod during the upward stroke is given back again during the downward stroke). In a decreasing wind, a windmill keeps running well below V_{start} until it stops at V_{stop}.

Classical "American" windmills normally have a relatively low design wind speed V_d so as to obtain a good starting behavior, thereby sacrifying some of the output.

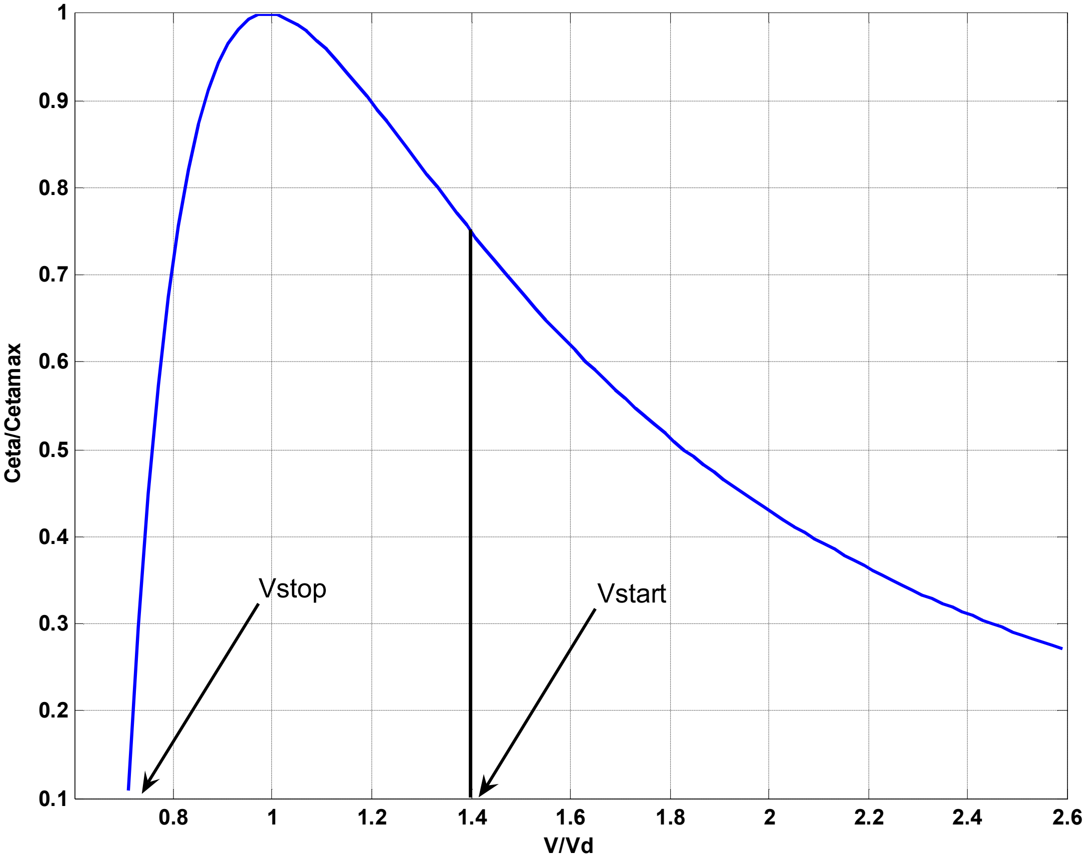


Figure 4-1: Starting and stopping speed for classical multi bladed wind mill.[2]

The probability of running in hysteresis region (between V_{stop} and V_{start}) by considering the wind speed history may be estimated by. [6]

$$f_{running} = \frac{f(V > V_{start})}{f(V < V_{stop}) + f(V > V_{start})} = \frac{\exp(-GX_{start}{}^{k})}{1 - \exp(-GX_{stop}{}^{k}) + \exp(-GX_{start}{}^{k})} \qquad 4.7$$

The simplest description of the starting behavior of a water pumping windmill is the static description, in which the starting torque of the rotor is equal to the maximum torque required by the pump at the starting wind speed V_{st}

$$T_{Rotor} = T_{Pump(\max)}$$

$$C_{Qst}\frac{1}{2}\rho A V_{st}{}^{2}R=\frac{1}{2}s\rho_{w}gHA_{P}=T_{pump}$$

The maximum torque of the pump is π times its average torque [3], and the average torque is equal to the torque T_d produced by the rotor at its design wind speed from assumption 1 above.

Torque and power coefficients can be related as $C_P=\lambda C_Q$.

$$C_{Tst}\frac{1}{2}\rho A V_{st}{}^{2}R=\pi C_{Td}\frac{1}{2}\rho\ V_{d}{}^{2}AR=C_{d}$$

$C_{Tst}\rho A V_{st}{}^{2}R=\pi\frac{C_{P\max}}{\lambda_{d}}\rho\ V_{d}{}^{2}AR$, solving for V_{st}.

$$V_{st}=V_{d}\sqrt{\frac{\pi C_{P\max}}{\lambda_{d}C_{Tst}}} \qquad 4.8$$

In this paper classical multi-bladed wind mills are considered having design tip speed ratio (λ_d) =1, maximum power coefficient ($C_{P\max}$) =0.32 and starting torque coefficient (C_{Tst}) =0.5.The resulting starting (cut-in speed) should be

$$V_{st}=1.4*V_{d} \qquad 4.9$$

This means that the wind mill needs a gust of wind with a speed about 1.4 times the design wind speed to start pumping water.

Enlighten of the overall performance of wind pumping Fig 4.1, the stopping wind speed is calculated as

$$V_{stop}=0.73*V_{d} \qquad 4.10$$

4.4 Rotor Performance of Wind Pump

The power developed by the system for pumping water P(V) is given by

$$P(V) = C_P \eta \frac{1}{2} \rho_a A V^3 \qquad 4.11$$

In this model a direct coupled mechanical wind pump with piston pump will be the system in consideration, having a cut-out velocity of 10m/s. The system has no constant power production regime or rated power, it simply cuts-out at velocity greater than 10m/s. This is due to low availability of wind speeds greater than 10m/s and such systems are abundantly installed all over the world becoming cost effective due to absence of back-gearing transmission mechanism. Moreover such kinds of systems are found today in the market extensively with reasonable cost.

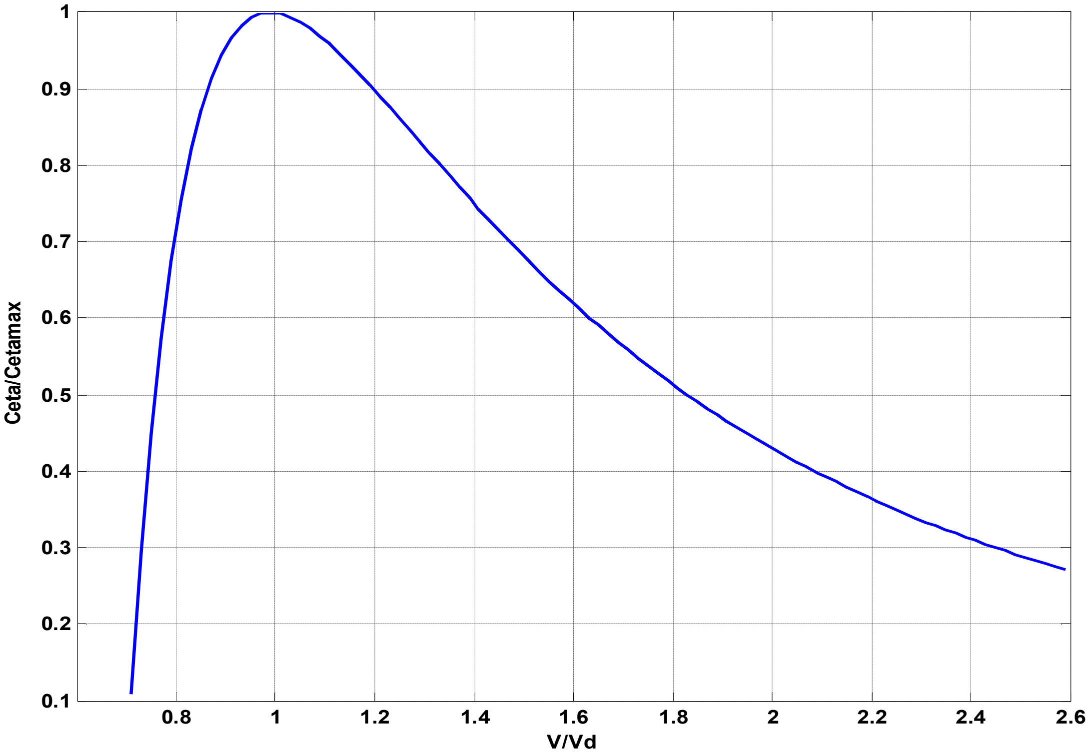


Figure 4-2: Overall performance coefficient for classical multi bladed piston pump

The overall performance coefficient of a wind rotor coupled to a reciprocating pump can be modeled as

$$C_P\eta = 4C_{Pd}\eta_{(T,P)}[1-K_O\left(\frac{V_I}{V}\right)^2]K_O\left(\frac{V_I}{V}\right)^2 \tag{4.12}$$

Where: $C_{pd}\eta$ is overall efficiency at design condition
K_0 is a constant 0.25
V_I is cut-in speed

Substituting Eq. (4.11) in to Eq. (4.10), a model equation for rotor power output can be expressed as,

$$P_V = 2C_{Pd}\eta_{(T,P)}\rho_a AV^3[1-K_O\left(\frac{V_I}{V}\right)^2]K_O\left(\frac{V_I}{V}\right)^2 \tag{4.13}$$

4.5 Reciprocating Pump Analysis

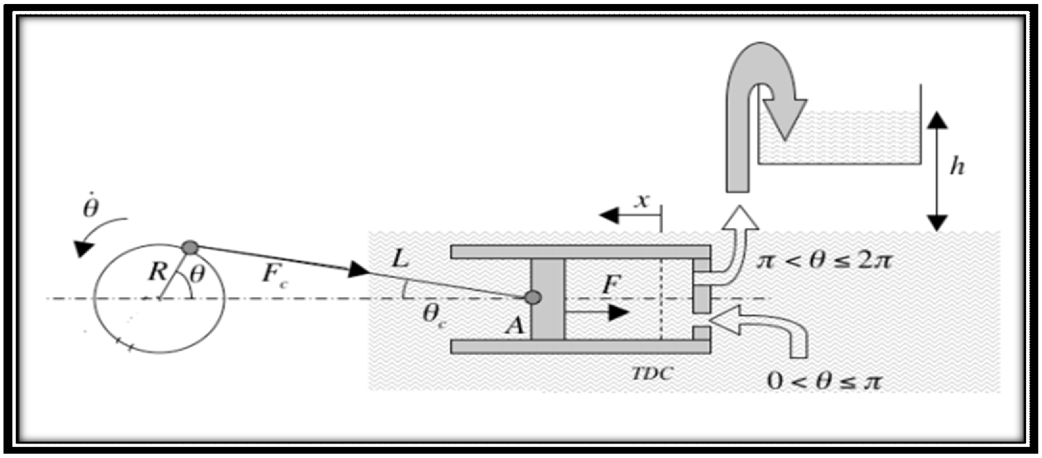


Figure 4-3: Reciprocating pump system.[10]

Consider a single cylinder - single acting piston pump consisting a slider-crank mechanism with connecting rod of length L and crankshaft of radius R moving a single piston of cross section area A along a straight path measured along the coordinate x from top-dead-center(TDC). The geometry yields

$$x = L + R - [\sqrt{L^2 - R^2 \sin^2 \theta} + R\cos\theta] \qquad 4.14$$

Where θ is the crank angle with $\theta = 0$ at TDC. In the limit of large L/R, the motion is nearly sinusoidal with $x \cong R(1-\cos\theta)$ and velocity $\dot{x} \cong R\dot{\theta}\sin\theta$. If the cylinder intakes water with $0 < \theta < \pi$ and exhausts it with $\pi < \theta < 2\pi$, and if the angular velocity is steady ($\dot{\theta}$ = constant), then the mean volume flow rate over an entire cycle is

$$\dot{Q} \cong -AR\dot{\theta}\frac{1}{2\pi}\int_{\theta=\pi}^{\theta=2\pi} \sin\theta d\theta = \frac{AR\dot{\theta}}{\pi} \qquad 4.15$$

If fluid inertia is neglected, the only force on the piston during the exhaust stroke is constant and equal to ρwghA, where h is the required height to lift water. Thus the instantaneous power required to lift water is $P = \rho_w ghA\dot{x}$ and its average is

$$P = \rho_w gh\dot{Q} = \rho_w gh\frac{AR\omega}{\pi} \qquad 4.16$$

4.6 Integrated Wind Regime, Rotor and Pump Output Model

Energy produced by the rotor at a give site at any wind speed over a period will be estimated by introducing the wind regime characteristics. [2]

$$E_I = f_{runnig}P_v f(V)dV + P_V f(V)dV \qquad 4.17$$

Substituting Equation 2.6,4.7,4.11 and 4.12 ,it yields

$$E_I = 2(C_P\eta)_{\max}\rho_a AV^3[[1 - K_0(\frac{V_I}{V})^2]K_0(\frac{V_I}{V})^2(\frac{k}{c})(\frac{v}{c})^{k-1}\exp\left[-(\frac{v}{c})\right]^k +$$

$$f_{running}[1 - K_0(\frac{V_I}{V})^2]K_0(\frac{V_I}{V})^2(\frac{k}{c})(\frac{v}{c})^{k-1}\exp\left[-(\frac{v}{c})\right]^k] \ldots\ldots\ldots\ldots\ldots\ldots 4.18$$

The hydraulic power (P_H) needed by the pump is

$$P_H = \rho_w g Q_P H \qquad 4.19$$

Equating with equation 4.17 and solving for the discharge Q

$$Q_P = 2(C_P\eta)_{\max}\rho_a A V^3[[1 - K_0(\frac{V_I}{V})^2]K_0(\frac{V_I}{V})^2(\frac{k}{c})(\frac{v}{c})^{k-1}\exp\left[-(\frac{v}{c})\right]^k + \qquad 4.20$$

$$f_{running}[1 - K_0(\frac{V_I}{V})^2]K_0(\frac{V_I}{V})^2(\frac{k}{c})(\frac{v}{c})^{k-1}\exp\left[-(\frac{v}{c})\right]^k]]\frac{1}{H\rho_w g}$$

4.7 Matching Rotor and Pump

When installing a wind pump it is important to match the characteristics of the pump and the wind machine. A good interaction between pump and rotor is essential. The most common type of pump used for water pumping in conjunction with a windmill is the reciprocating or piston pump. The piston pump tends to have a high torque requirement on starting because, when starting, the rotor has to provide enough torque to overcome the weight of the pump rods and water in the rising main. Once the rotor is turning, the torque requirement decreases because of the momentum of the revolving rotor. The wind speed can then drop to about 2/3 of the start-up wind speed before the wind pump will stop.

Choosing a large pump leads to a high output but a low availability. The choice of a small pump improves availability but reduces output. In matching a pump to a windmill, one needs to establish the best possible compromise between output and availability.

The windmill-pump system will operate at the points of intersection of windmill curves and pump curve, where the pump torque equals the rotor torque. One sees immediately that a piston pump leaves a large part of the power available from the wind unused, especially at higher speeds. The windmill will operate at its maximum power coefficient for only one wind speed V_d, for which the pump characteristic intersects the rotor power curve

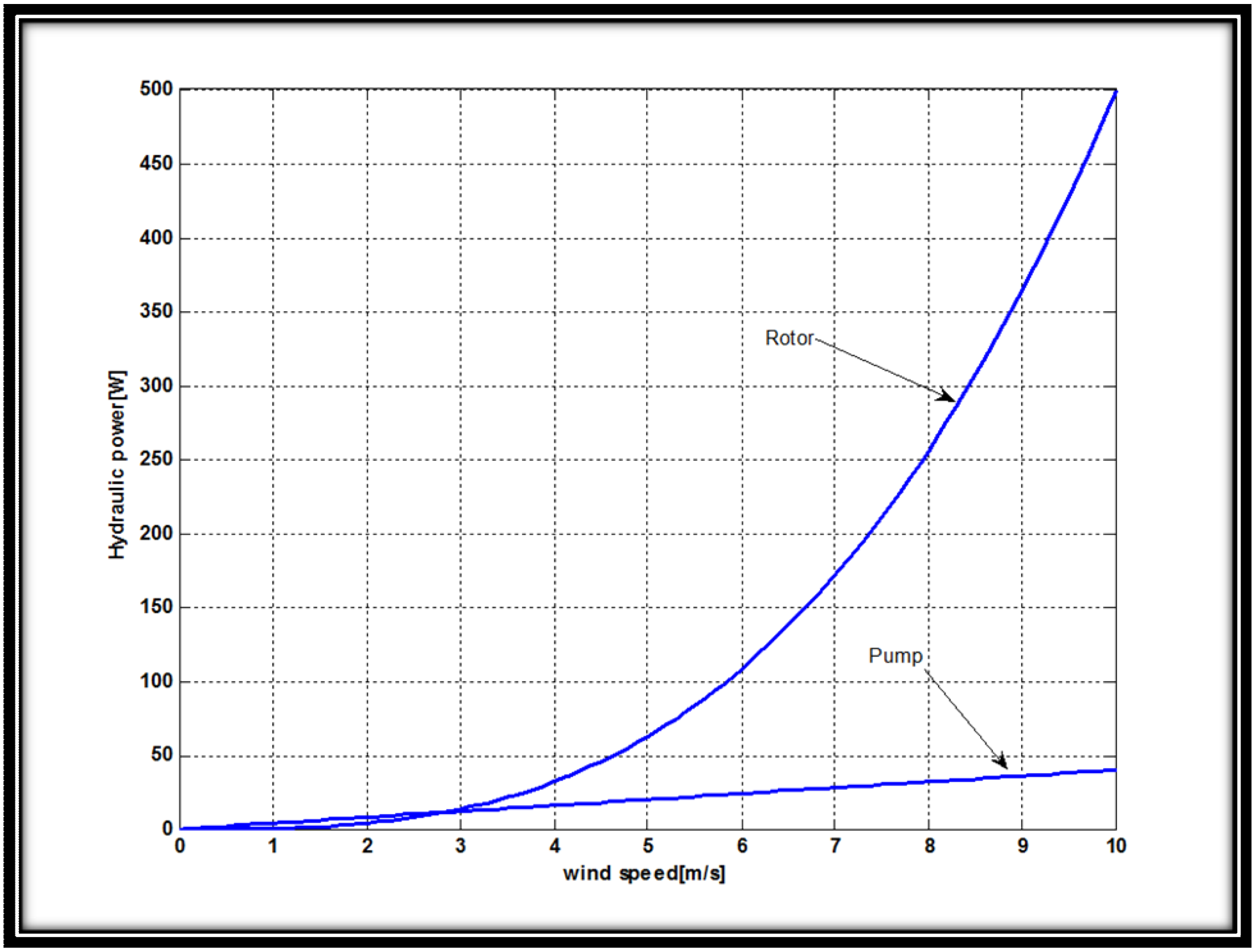


Figure 4-4: Typical wind rotor and hydraulic power curves

4.8 The Energy Output in a Weibull Wind Regime

The long-term output depends on the hydraulic power of the wind pump and the wind regime at the site. It is assumed that this is to be governed by a Weibull distribution with an average wind speed V_{av}. The choice of the design speed V_d related to the average wind speed V_{av} determines the matching of the wind pump to the local conditions and whether it performs satisfactorily. A dimensionless wind speed X is therefore introduced:

$$X = \frac{V}{V_{av}} \qquad 4.21$$

Then the dimensionless design wind speed is X_d and the hydraulic output becomes

$$P(X) = 2C_{Pd}\eta_{(T,P)}\rho_a A X^3 V_{av}{}^3[1 - K_O\left(\frac{1.4X_d}{X}\right)^2]K_O\left(\frac{1.4X_d}{X}\right)^2 \qquad 4.22$$

With f(x) the weibull probability density function, the hydraulic energy output of the wind pump (E) averaged over a period T is:

$$E = T[\int_{Xstop}^{X_{Start}} f_{running} P(x) f(x) dx + \int_{Xstart}^{Xo} P(x) f(x) dx] \qquad 4.23$$

Introducing the output of an ideal windmill which always operates at its optimum efficiency $(C_P\eta)_{max}$, to define the reference output (E_{ref}):

$$E_{ref} = T(\frac{1}{2}\rho A(C_p\eta)_{\max} V_{av}{}^3 K_E) \qquad 4.24$$

Where K_E is energy pattern factor, which represents the difference in output estimated by using $V_{av}{}^3$ instead of $(V^3)_{av}$,expresses as gamma function.[2]

$$K_E = \frac{\Gamma(1+\frac{3}{k})}{\Gamma^3(1+\frac{1}{k})} \qquad 4.25$$

The Weibull probability density function f(v), can be written in a dimensionless wind speed X as: [11]

$$f(x) = GkX^{k-1}\exp(-GX^k) \qquad 4.26$$

Where G is gamma function described as $G = \Gamma^k(1+\frac{1}{k})$

The hydraulic energy output of the wind pump (E) averaged over a period T can be written in a compact form as:

$$P(X) = 4E_{ref}\frac{X^3}{K_E}[1-K_O\left(\frac{1.4X_d}{X}\right)^2]K_O\left(\frac{1.4X_d}{X}\right)^2 \qquad 4.27$$

Here the energy production range is between stopping wind speed and cut-out wind speed of the system, though it starts at cut-in speed. Hence total energy production is given as:

$$E = T[\int_{Xstop}^{Xstart} f_{running}P(x)f(x)dx + \int_{XStart}^{Xo} P(x)f(x)dx]$$

4.28

Substituting equations and rearranging gives:

$$\frac{E}{E_{ref}} = \frac{1}{K_E}[\int_{Xstop}^{X_{Start}} f_{ruuning}4X^3(1-k_0\left(\frac{1.4X_d}{X}\right)^2)K_0\left(\frac{1.4X_d}{X}\right)^2 * GkX^{k-1}\exp(-GX^k)dX \; +$$

$$\int_{Xstart}^{X_O} 4X^3(1-k_0\left(\frac{1.4X_d}{X}\right)^2)K_0\left(\frac{1.4X_d}{X}\right)^2 * GkX^{k-1}\exp(-GX^k)dX \;\;] \qquad 4.29$$

Energy production coefficient which is a key parameter in matching wind rotor and pump in a wind regime over a period of time is given as:

$$C_E = \frac{E}{E_{ref}} \qquad 4.30$$

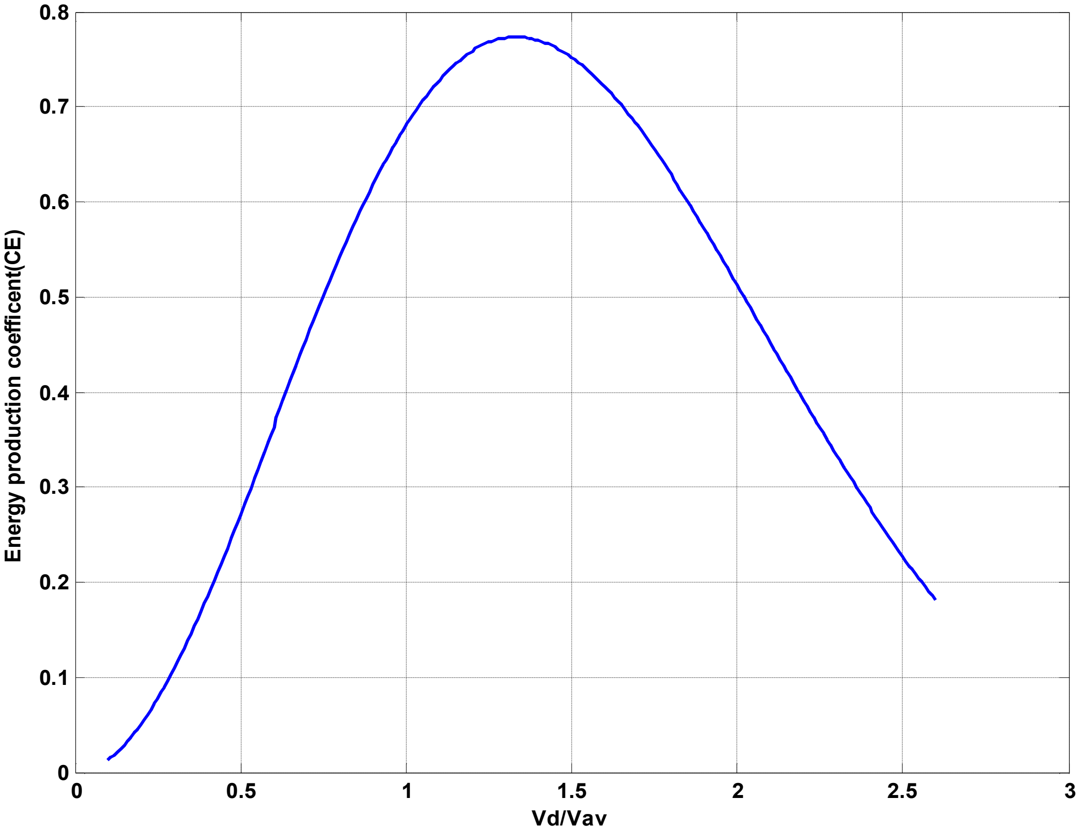


Figure 4-5: Energy production coefficient for a range of matching ratio (Weibull parameter, k=2 and V_O=10m/s)

4.9 Availability

The availability τ of the power from the windmill is defined as the fraction of the total time at which the wind speed is sufficient to operate the machine. The windmill cannot operate during all hours with relative speeds between 0 and X_{in} and with relative speeds higher than X_{out}. The cumulative distribution function is given as:

$$F(V) = 1 - \exp\left[-(\frac{V}{c})\right]^{k} \qquad 4.31$$

In terms of the dimensionless parameter X, it can be describe as:

$$F(X) = 1 - \exp(-GX^{k}) \quad 4.32$$

$$\tau = F(X_{out}) - F(X_{in}) = \exp(-GX_{in}{}^{k}) - \exp(-GX_{out}{}^{k}) \quad 4.33$$

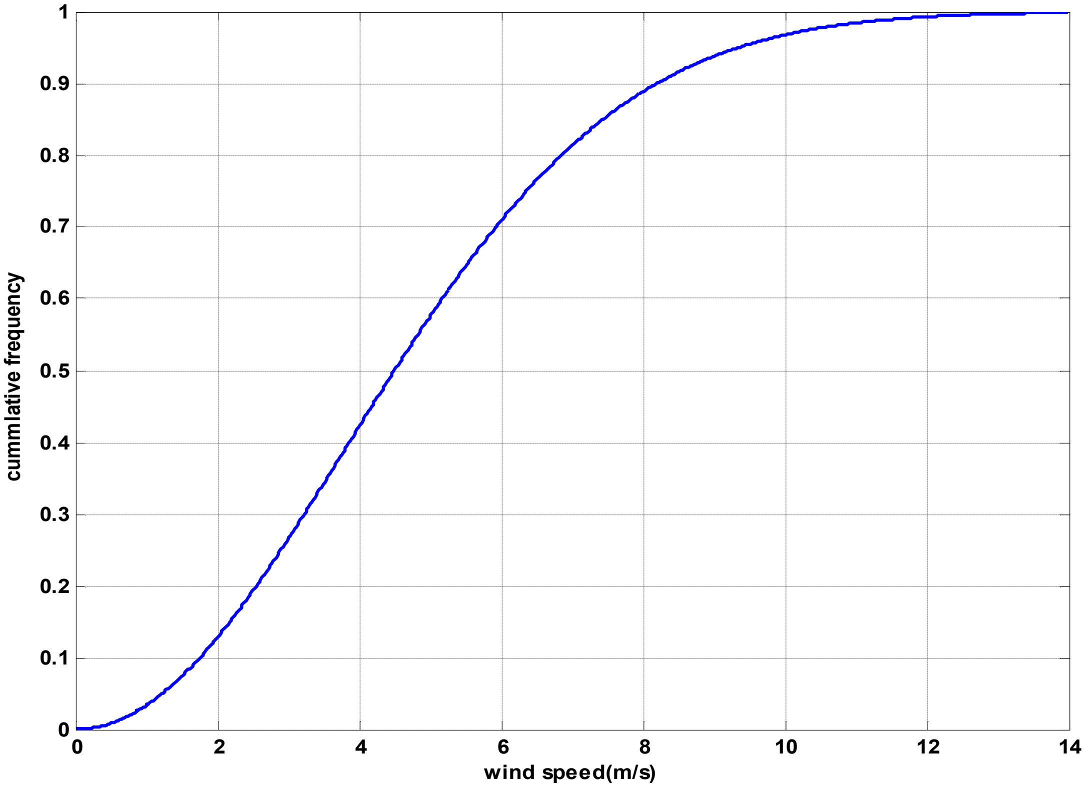


Figure 4-6: Typical cumulative frequency function for (k=2 and c=5.4)

CHAPTER 5

5. Feasibility Study of Wind Pumping

5.1 Identification of Design Month for Selected Sites

Based on the wind potential assessment done in chapter three, the feasibility of wind pumping for village water supply and irrigation for a model community of about 500 people (100 households, with five family members in each) at selected area will be carried out.

The locations are Assosa, 10 ″ 01'N, 34″ 31'E, 1600 m; Mekele, 13 ″33'N, 39″ 29'E, 2130 m; Nekemt, 9 ″05'N, 36″ 37'E, 2080 m and Jijiga 09″20'N, 42″ 47'E, 1775 m.

5.1.1 Design Month for Water Supply

To determine the design month of the year in a wind regime, monthly average wind speed and hydraulic power requirement should be known first. For village water supply the water remand is constant throughout the year, hence the design month is the month with lowest average wind speed (the month were the system is heavily loaded). The most probable rainy months are July and August. During the rainy season, water consumption from the wind pump is expected to be shared by rain water ponds. Hence the system will not be loaded in these months. When the lowest monthly average falls on these months, the next month with lowest average wind speed will be considered (design month).

Table 5-1: Monthly average wind speed and design month for four locations

Mekele												
Month	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nove	Dec
Average wind Speed	4.34	5.87	6.27	6.29	4.45	3.19	3.16	2.54	2.91	5.62	6.27	6.42
Design month	**September**											
Assosa												
Month	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nove	Dec
Average Wind Speed	4.55	4.80	4.22	4.17	4.33	3.74	3.05	2.95	3.20	2.98	2.50	3.4
Design month	**November**											
Jijiga												
Month	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nove	Dec
Average Wind Speed	4.52	3.40	2.75	3.14	3.34	4.35	4.51	3.97	3.17	2.64	3.44	3.25
Design month	**October**											
Nekemt												
Month	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nove	Dec
Average Wind Speed	1.81	2.08	2.09	2.35	2.25	1.65	1.56	1.79	1.63	1.75	1.57	1.89
Design month	**November**											

5.1.2 Design Month for Irrigation

To determine the design month of the year in a wind regime, monthly average wind speed and hydraulic power requirement should be known first. In most parts of the country, rainy season starts around June and ends in August. September and May are considered as usually harvesting period for rainy season and land preparation for irrigation.

Duringrainy season, water demand from the pump for irrigation is zero. Hence the system will not be loaded in these months. Assuming the water requirement is constant in the growing stage of the crop, as in the case of water supply, the design month will be the month with the lowest average wind speed.

Table 5-2: Monthly average wind speed and design month for three locations

Mekele												
Month	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nove	Dec
Average wind Speed	4.34	5.87	6.27	6.29	***4.45***	***3.19***	***3.16***	***2.54***	***2.91***	5.62	6.27	6.42
Design month	**January**											
Assosa												
Month	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nove	Dec
Average Wind Speed	4.55	4.80	4.22	4.17	***4.33***	***3.74***	***3.05***	***2.95***	***3.20***	2.98	2.50	3.4
Design month	**November**											
Jijiga												
Month	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nove	Dec
Average Wind Speed	4.52	3.40	2.75	***3.14***	***3.34***	***4.35***	***4.51***	***3.97***	***3.17***	2.64	3.44	3.25
Design month	**October**											
Nekemt												
Month	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nove	Dec
Average Wind Speed	1.81	2.08	2.09	***2.35***	***2.25***	***1.65***	***1.56***	***1.79***	***1.63***	1.75	1.57	1.89
Design month	**November**											

5.2 Wind Pump Sizing for Rural Water Supply

5.2.1 Water Requirement for Domestic Supply

The daily demand for village water supply in Ethiopia can be taken as 20liter per capita. For the model community, the daily total demand is assumed to be 10m^3 for 500 people. In order to limit the time spent on collecting and carrying water, a single pump or water point will supply the demand [1]. July and August are the most probable rainy month. During the rainy season, water consumption from the wind pump is expected to be shared by rain water ponds.

5.2.2 Rotor Diameter Determination

The rotor diameter depends on the design wind speed while the wind speed depends on the characteristics of wind regime. The most probable wind speed and speed contributing maximum energy output in the regime is different due to the cubic relationship in power output. Due to several constraints, such as availability and output optimization it is difficult to achieve the design speed as close to the maximum energy speed in a regime. The range of total head (static and dynamic) in consideration is 20 to 80m at 20m interval.

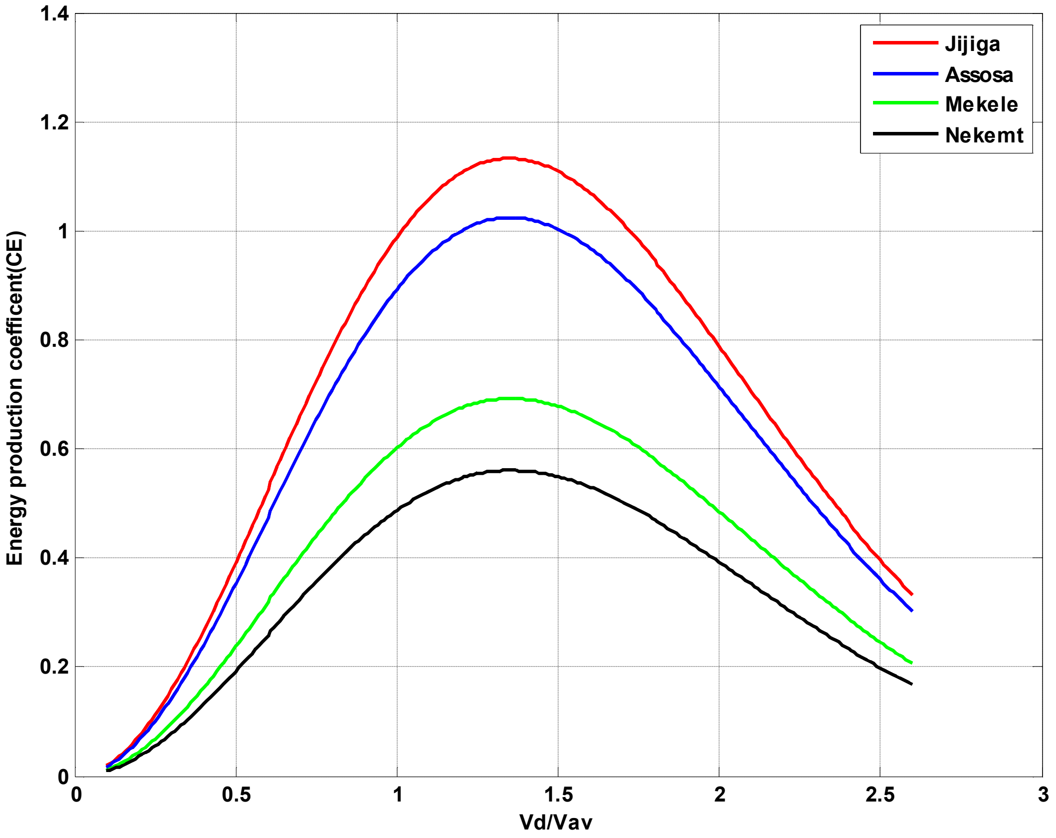


Figure 5-1: Energy production coefficient for a range of matching ratio in the critical month (cut-out wind speed V_O=10m/s)

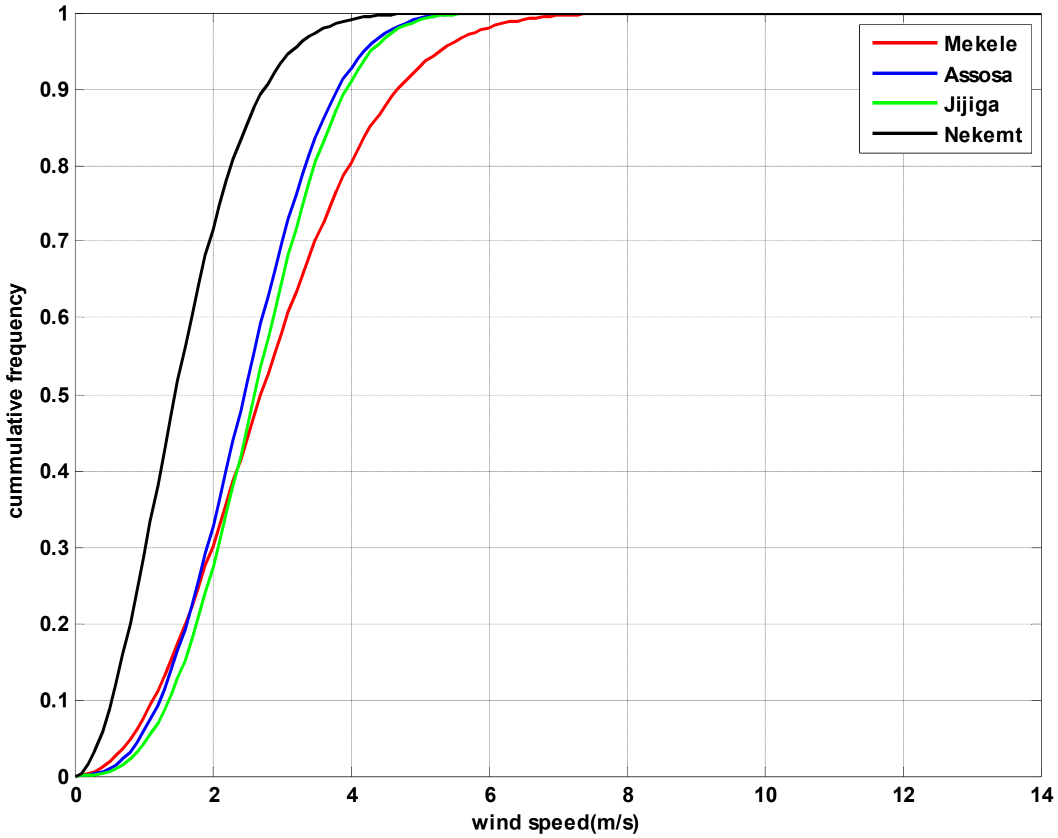


Figure 5-2: Cumulative frequency function for the critical month

Considering classical multi bladed windmill and allowing for better availability with low cut-in velocity, energy production coefficient for the respective wind regimes with matching ratio of 0.6 is found to be 0.57 for Assosa and 0.6 for Jijiga. For Mekele with matching ratio of 0.7 energy production coefficient is found to be 0.4. Maximum overall efficiency of wind pump $(C_P\eta)_{max}$ is taken as 0.3 at design point.

Equating the hydraulic and the rotor power

$$P(V) = C_E K_E (C_P \eta)_{\max} \frac{1}{2} \rho_a A V_{av}{}^3 = P_H = Q \rho_w g H$$

$$A = \frac{2Q\rho_w gH}{(C_P\eta)_{\max}\, \rho_a V_{av}{}^3 C_E K_E}$$, hence Rotor diameter $D = \sqrt{\frac{4A}{\pi}}$

Table 5-3: Rotor diameter sizing summery for each station

	C_E	K_E	V_{av}	Daily demand(m^3)	Rotor Diameter(m)			
					H=20m	H=40m	H=60m	H=80m
Jijiga	0.78	1.42	2.64	10	3.5	4.5	5.5	6.5
Assosa	0.70	1.48	2.5	10	3.5	4.5	6	6.5
Mekele	0.4	1.78	2.91	10	3	4.5	5.5	6
Nekemt	0.36	2.01	1.57	10	8.5	12.0	14.5	17

5.2.2 Determination of Pump Parameters

Equating the rotor and hydraulic power and solving for swept volume (V_s)

$$P(V) = (C_P\eta)_{\max}\frac{1}{2}\rho_a A V_d{}^3$$

$$P_H = Q\rho_w gH = \eta_v V_s N\rho_w gH$$

$$= \eta_v V_s \frac{\omega}{2\pi} i\rho_w gH$$

$V_s = \dfrac{V_d{}^2 R^3 i\pi^2 (C_P\eta)_{\max}\rho_a}{\eta_v\lambda\rho_w gH}$, $V_s = \dfrac{\pi D_P{}^2 s}{4}$, where D_P is Pump diameter ,s is pump stroke and i is transmission ratio.

For specified swept volume standard stroke and pump diameter can be selected from standard chart [Appendix]

Table 5-4: Pump stroke and diameter sizing summery for each station

	V_d	λ_d	Cut-in velocity	Availa bility	η_v (%)	Daily demand (m^3)	Pump Stroke and Diameter(mm)		
							R=1.8	R=2.4	R=3
Jijiga	2.11	1	2.95	78%	90	10	100,82	150,72	150,83
Assosa	2.0	1	2.80	72%	90	10	100,77	150,69	150,78
Mekele	2.04	1	2.85	79%	90	10	100,79	150,70	150,80

5.3 Wind Pump Sizing for Irrigation

5.3.1 Water Requirement for Irrigation

The amount of water needed to irrigate a given area depends on a number of factors. The most important of these are:

- Nature of crop, crop growth cycle,
- Climatic conditions,
- Type and condition of soil,
- Topography of the terrain,
- Conveyance efficiency,
- Field application efficiency and
- Water quality.

The pumped volume required per day for irrigation can be estimated using the equation[7]:

$$V_{Ol} = \frac{Plot * Canopy * Demand}{Eff} \qquad 5.1$$

Where:V_{ol} is the pumped volume [m^3/day]; Plot is the plot size [ha]; Canopy is the canopy fraction (the fraction of the plot covered with plant branches and leaves); Demand is the crop water demand; and Eff is the field application efficiency.

Based on World Bank manual [1], as a rule of thumb, 5-6 lit/day/m^2 of crop canopy in cooler or more humid climates, and 7-8 lit/day/m^2 in hot, dry climates is recommended. This figure can be converted to its equivalent in m^3/day/ha of crop canopy by simply multiplying is by a factor of 10. [m/day/ha].

The plot size is assumed to be 1/4 hectar, and the demand for all villages with hot and dry climates is taken as 7.5lit/day/ha. Typical value for crop canopy is 80% and irrigation efficiency in hot and dry climates is 60%.[3]

The required pumping volume per day is:

$$V_{Ol} = \frac{2500 * 0.8 * 7.5}{0.6} = 25m^3$$

5.3.2 Rotor Diameter Determination

The rotor diameter depends on the design wind speed while the wind speed depends on the characteristics of wind regime. The most probable wind speed and speed contributing maximum energy output in the regime is different due to the cubic relationship in power output. Due to several constraints, such as availability and output optimization it is difficult to achieve the design speed as close to the maximum energy speed in a regime. The total head (static and dynamic) in consideration are 20 and 30m.

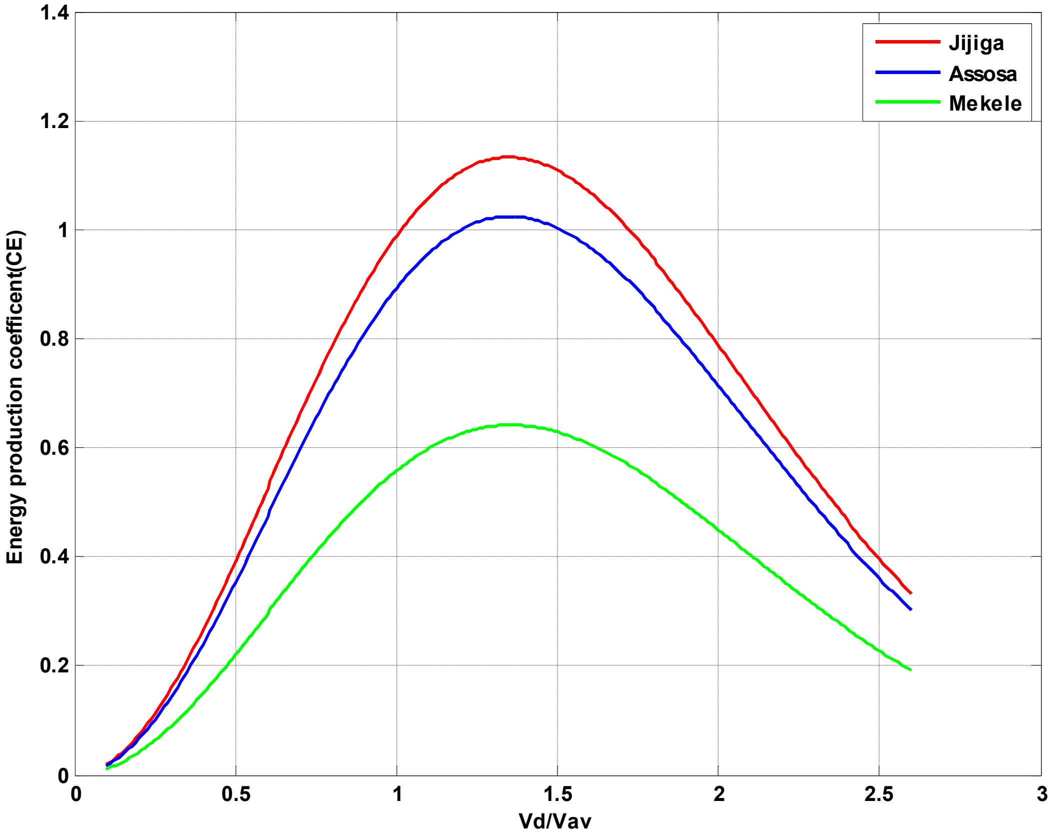


Figure 5-3: Energy production coefficient for a range of matching ratio in the critical month (cut-out wind speed V_O=10m/s)

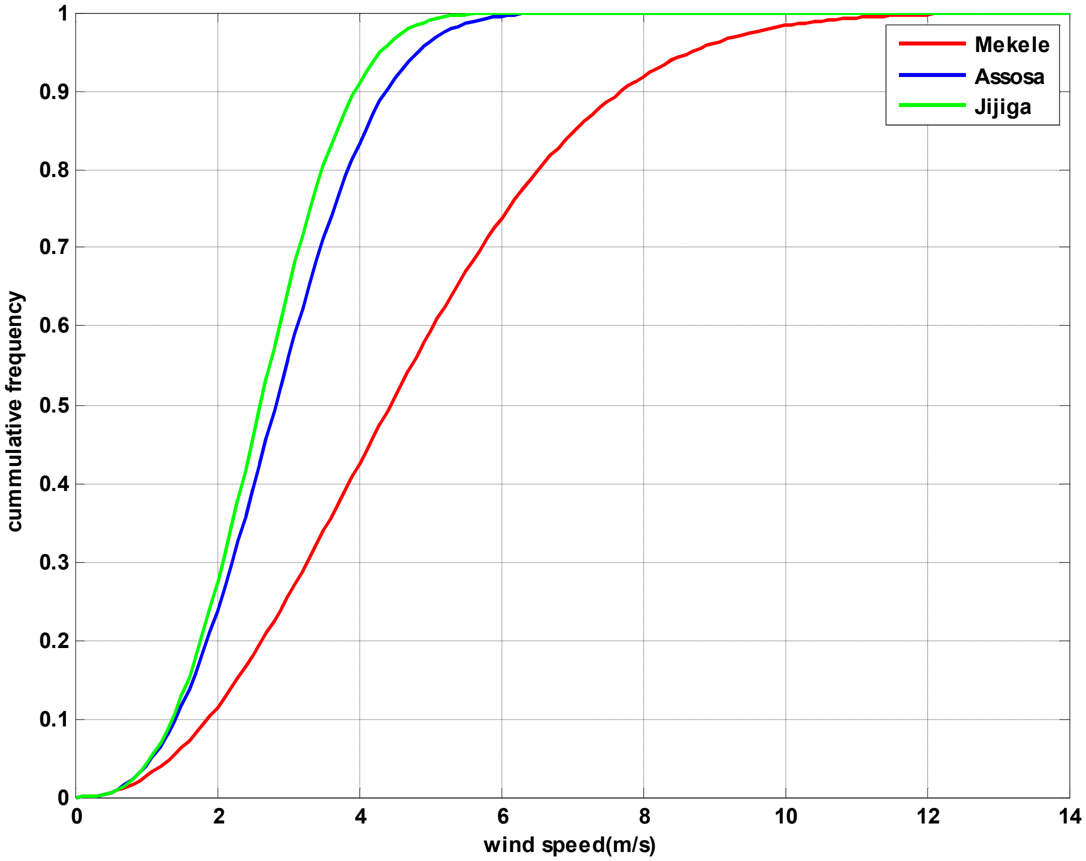


Figure 5-4: Cumulative frequency function for the critical month

Considering classical multi bladed windmill and allowing for better availability with low cut-in velocity, energy production coefficient for the respective wind regimes with matching ratio of 0.8 is found to be 0.72 for Assosa and 0.8 for Jijiga. For Mekele with matching ratio of 0.6 energy production coefficient is found to be 0.36. Maximum overall efficiency of wind pump $(C_P\eta)_{max}$ is taken as 0.3 at design point. For Nekemt the design month is the same for both applications.

Equating the hydraulic and the rotor power

$$P(V) = C_E K_E (C_P \eta)_{\max} \frac{1}{2} \rho_a A V_{av}{}^3 = P_H = Q \rho_w g H$$

$$A = \frac{2Q\rho_w gH}{(C_P\eta)_{\max}\rho_a V_{av}{}^3 C_E K_E}$$, hence Rotor diameter $D = \sqrt{\frac{4A}{\pi}}$

Table 5-5: Rotor diameter sizing summery for each station

	C_E	K_E	Availability	V_{av}	Daily demand(m^3)	Rotor Diameter	
						H=20m	H=30m
Jijiga	0.8	1.43	70%	2.64	25	4.5	5.5
Assosa	0.72	1.48	71%	2.5	25	5	6
Mekele	0.36	1.76	79%	4.34	25	3	3.5

5.3.2 Determination of Pump Parameters

Equating the rotor and hydraulic power and solving for swept volume (V_s)

$$P(V) = (C_P\eta)_{\max}\frac{1}{2}\rho_a A V_d{}^3$$

$$P_H = Q\rho_w gH = \eta_v V_s N \rho_w gH$$

$$= \eta_v V_s \frac{\omega}{2\pi}\rho_w gH$$

$$V_s = \frac{V_d{}^2 R^3 i\pi^2 (C_P\eta)_{\max}\rho_a}{\eta_v \lambda \rho_w gH}$$

Table 5-6: Pump stroke and diameter sizing summery for each stations

	V_d	λ_d	Cut-in velocity	η_v(%)	Daily demand(m^3)	Pump Stroke and Diameter(mm)		
						R=1.8	R=2.4	R=3
Jijiga	2.11	1	2.95	90	25			150,157
Assosa	2.0	1	2.80	90	25		150,80	150,111
Mekele	2.6	1	3.6	90	25	150,98		

5.4 Diesel Pump Sizing

The Diesel pump is sized by calculating the actual power required to lift water.

$P = \rho g H \dot{Q}$ [W]

Where:

ρ = density of water [kg/m^3]

g = gravitational acceleration [m/s^2]

H = total head [m]

Q = flow rate [m^3/s]

The following losses are added to the hydraulic power to calculate the overall shaft power required:

- ***Pump element efficiency***: Variable as a function of the head, a typical conservative value 60% is used. (Source: GW Orbit Pump catalogue)

- ***Friction losses in the rising main***: Variable as a function of the flow rate and the pipe diameter, a typical conservative value 6% is used.

- ***Rising main losses*****:** Due to a possibly non-linearity of taper threaded pipes (the quality of taper threaded pipe has become poorer over recent years and there is a good chance that the rising main is not perfectly straight, this "wobble" has efficiency, as well as maintenance implications). This factor can be considerable but is virtually impossible to predict or assess scientifically. It is taken as a fixed 5% value which is considered conservative.

- ***Windage losses***: Fixed at 10%. These are friction losses at the entry and exit of the belts into the pulleys.

- ***Derating of the Diesel engine for altitude and temperature*:** Fixed altitude (4% per 300m above sea level) and operating temperature (2% for every 5°C above 25°C).
- ***Engine load factor*:** The engine load factor is selected at 70%, providing the rated nominal power of the engine, and the Diesel pump will operate 6hours per day.

Table 5-7: Diesel pump sizing summery

	Altitude(m)	Diesel pump Rated power(KW)					
		Water supply(10m^3/day)				Irrigation(25m^3/day)	
		H=20m	H=40m	H=60m	H=80m	H=20m	H=30m
Jijiga	1775	0.26	0.51	0.77	1.02	0.64	0.96
Assosa	1600	0.26	0.51	0.77	1.02	0.64	0.96
Mekele	2130	0.26	0.51	0.77	1.02	0.64	0.96

Based on the instantaneous pump discharge equation derived under section 4.6, monthly total discharge is found for each application in each sites. In the following section the area under the curve represents the total monthly discharge expected in each sites at different total head.

5.5 Monthly Water Supply Discharge for Assosa

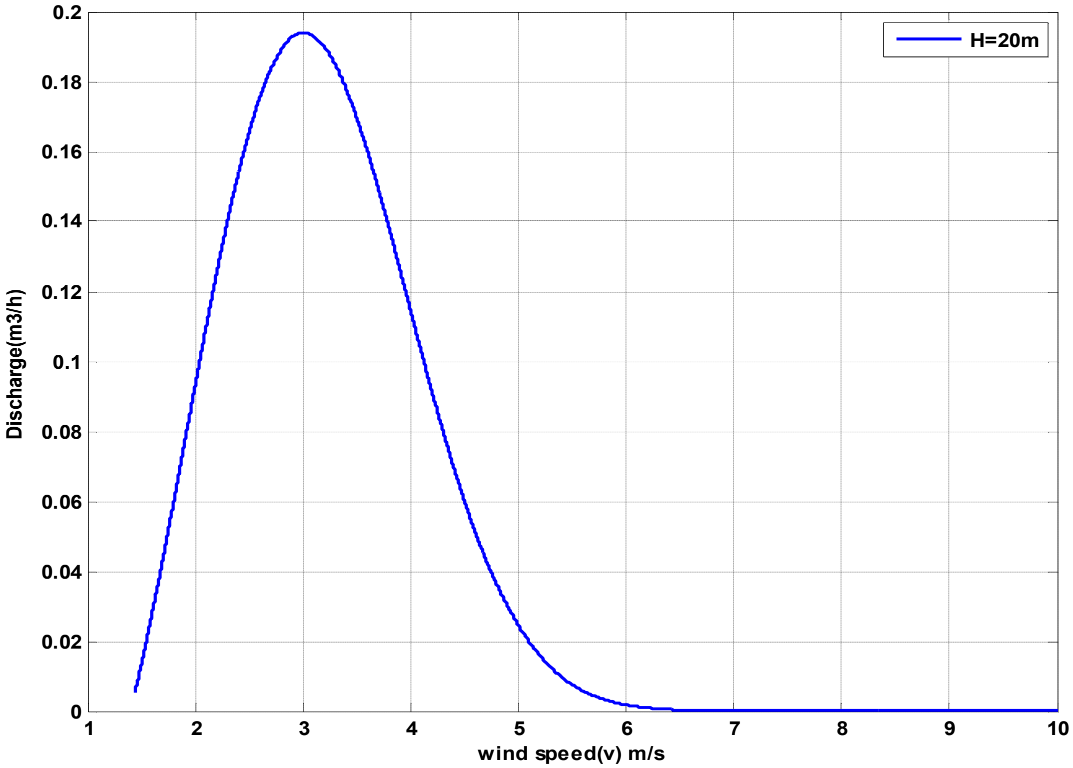


Figure 5-5: Expected discharge rate for the design moth of Assosa at 20m

Table 5-8: Daily expected discharge at different pumping head for Assosa.

Month	Shape parameter(k)	Scale parameter(c)	Discharge(m^3)			
			H=20m,D=3.5m	H=40m,D=4.5m	H=60m,D=5.5m	H=80m,D=6.5m
Jan	2.72	5.1	24	19.92	23.52	20.88
Feb	2.74	5.39	25.68	21.36	25.2	22.08
Mar	2.73	4.74	22.08	18.24	22.08	18.96
Apri	2.72	4.68	21.84	18	18.48	18.72
May	2.73	4.84	22.8	18.72	22.32	19.68
June	2.72	4.2	18.96	15.6	18.48	16.32
July	2.73	3.43	14.16	11.76	13.68	12.24
Aug	2.72	3.33	13.44	11.04	13.2	11.52
Sep	2.68	3.56	14.88	12.24	14.64	12.96
Oct	2.72	3.35	13.68	11.28	13.44	11.76
Nove	2.73	2.81	10.08	8.4	10.08	8.64
Dec	2.72	3.81	16.56	13.68	16.08	14.16

5.6 Monthly Water Supply Discharge for Mekele

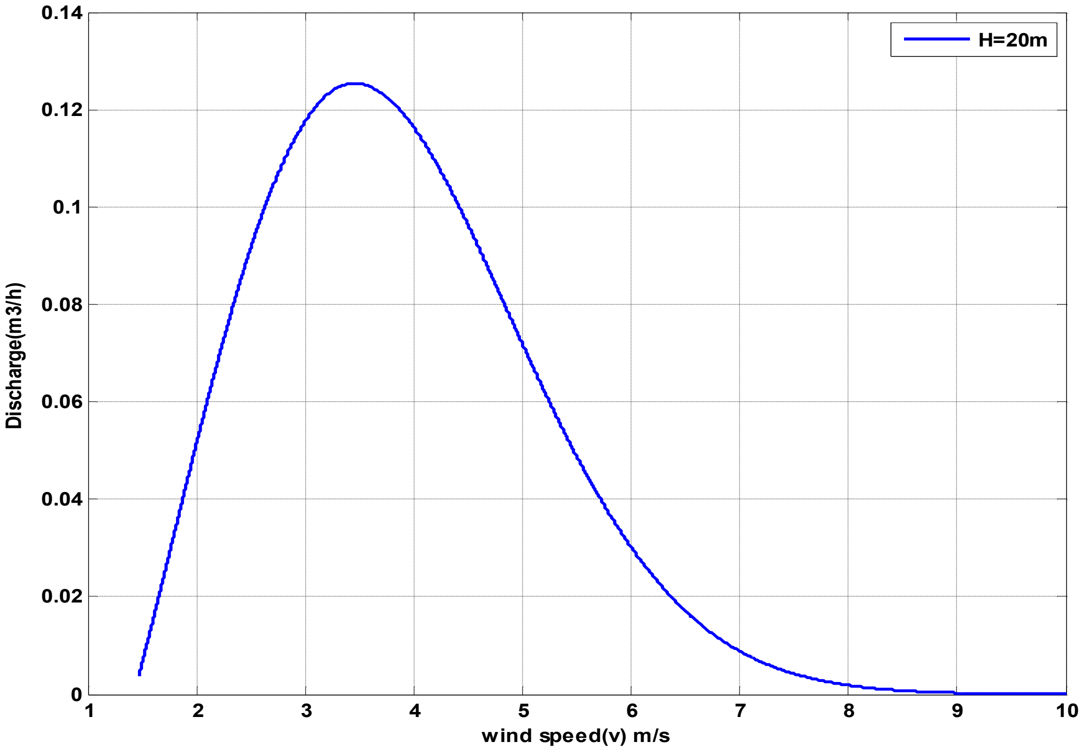


Figure 5-6: Expected discharge rate for the design month of Mekele at 20m

Table 5-9: Daily expected discharge at different pumping head for Mekele

Month	Shape parameter(k)	Scale parameter(c)	Discharge(m^3)			
			H=20m,D=3m	H=40m,D=4.5m	H=60m,D=5.5m	H=80m,D=6m
Jan	2.18	5.05	17.28	19.44	19.44	17.28
Feb	2.20	6.63	20.4	23.04	23.04	20.4
Mar	2.19	6.89	20.4	23.04	23.04	20.4
Apri	2.18	7.19	20.4	23.04	23.04	20.4
May	2.18	5.24	18	20.16	20.16	18
June	2.18	3.72	12	13.44	13.44	12
July	2.17	3.62	11.52	12.96	12.72	11.52
Aug	2.18	2.88	7.92	8.88	8.88	8.16
Sep	2.15	3.2	9.6	10.56	10.56	9.6
Oct	2.17	6.25	19.92	22.56	22.32	19.92
Nove	2.2	7.16	20.64	23.04	23.04	20.64
Dec	2.17	7.15	20.4	22.8	22.8	20.4

5.7 Monthly Water Supply Discharge for Jijiga

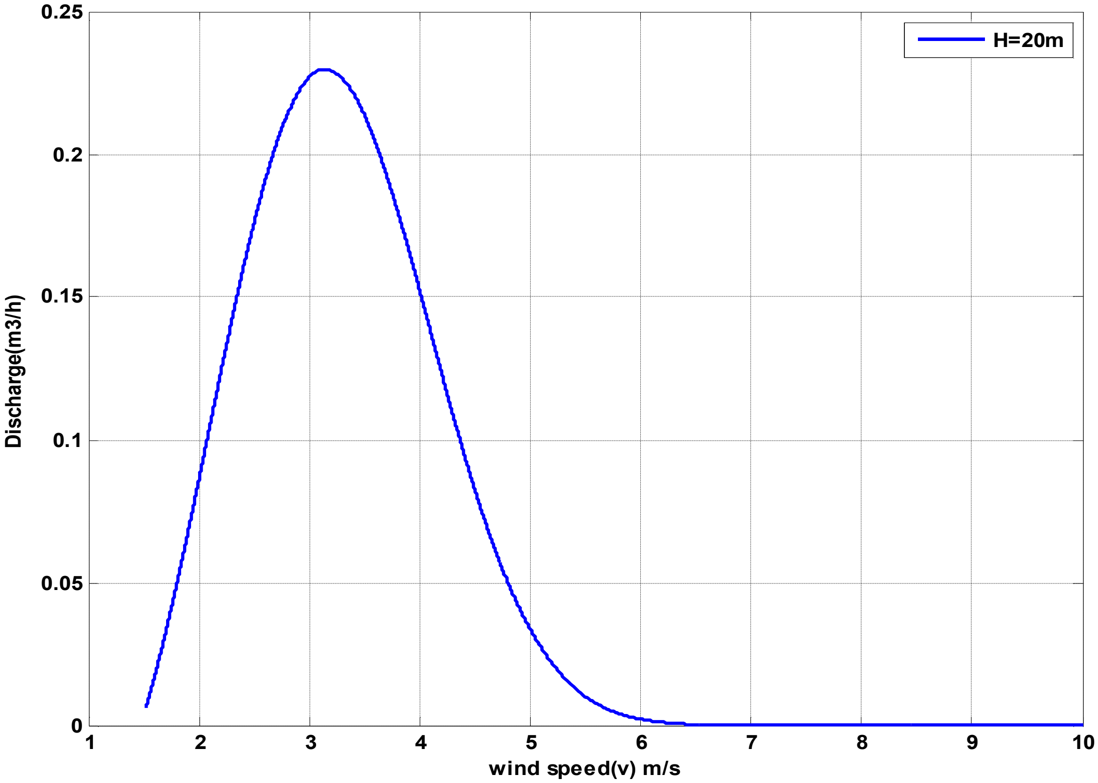


Figure 5-7: Expected discharge rate for the design month of Jijiga at 20m

Table 5-10: Daily expected discharge at different pumping head for Jijiga

Month	Shape parameter(k)	Scale parameter(c)	Discharge(m^3)			
			H=20m,D=3.5m	H=40m,D=4.5m	H=60m,D=5.5m	H=80m,D=6.5m
Jan	2.92	5.05	26.16	21.84	21.6	22.8
Feb	2.91	3.82	18	14.88	14.88	15.6
Mar	2.93	3.09	12.96	10.56	10.56	11.04
Apri	2.91	3.52	15.84	13.2	13.2	13.68
May	2.91	3.75	17.52	14.4	14.4	15.12
June	2.91	4.88	25.2	20.88	20.88	21.84
July	2.92	5.06	26.4	21.84	21.84	22.8
Aug	2.92	4.45	22.32	18.48	18.48	19.2
Sep	2.89	3.52	15.84	13.2	13.2	13.68
Oct	2.92	2.96	12	9.84	9.84	10.32
Nove	2.94	3.86	18.24	15.12	15.12	15.84
Dec	2.89	3.63	16.8	13.68	13.68	14.4

5.8 Monthly Irrigation Discharge for Assosa

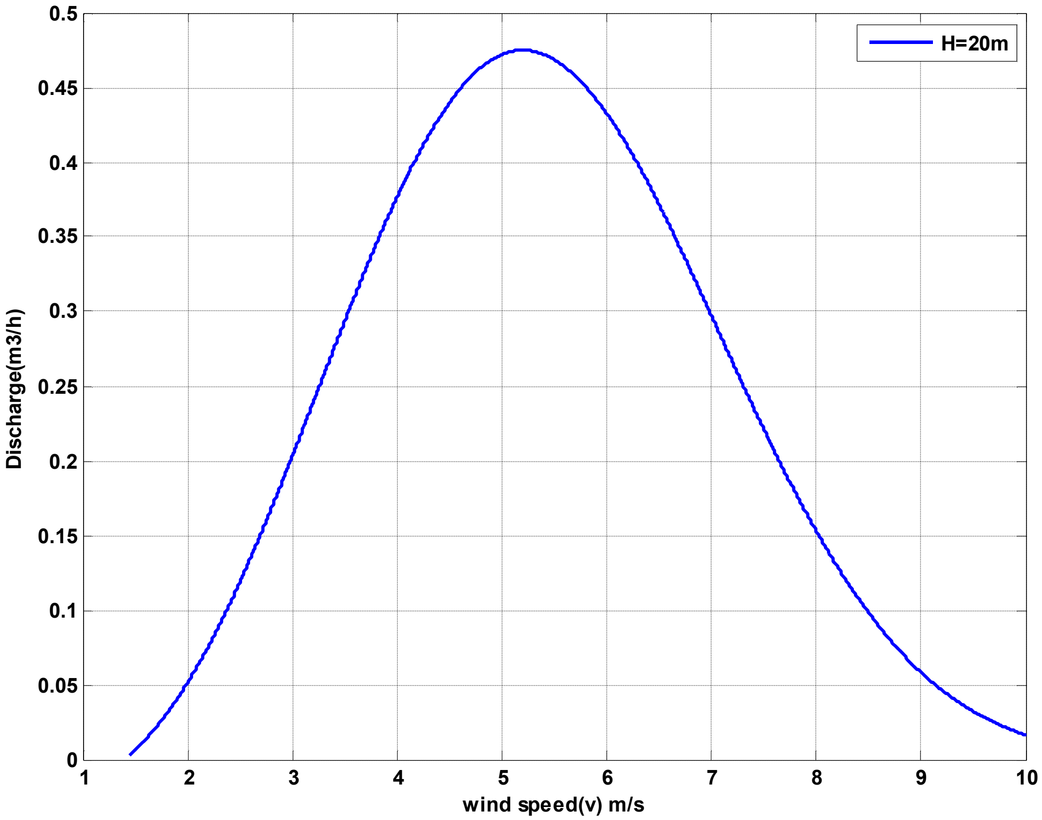


Figure 5-8: Expected discharge rate for the design month of Assosa at 20m

Table 5-11: Daily expected discharge at different pumping head for Assosa

Month	Shape parameter(k)	Scale parameter(c)	Discharge(m^3)	
			H=20m,D=5m	H=30m,D=6m
Jan	2.72	5.1	49.2	47.28
Feb	2.74	5.39	52.56	50.4
Mar	2.73	4.74	45.12	43.2
Apri	2.72	4.68	44.4	42.72
Oct	2.72	3.35	27.84	26.64
Nove	2.73	3.23	26.16	25.2
Dec	2.72	3.81	33.6	32.4

5.9 Monthly Irrigation Discharge for Mekele

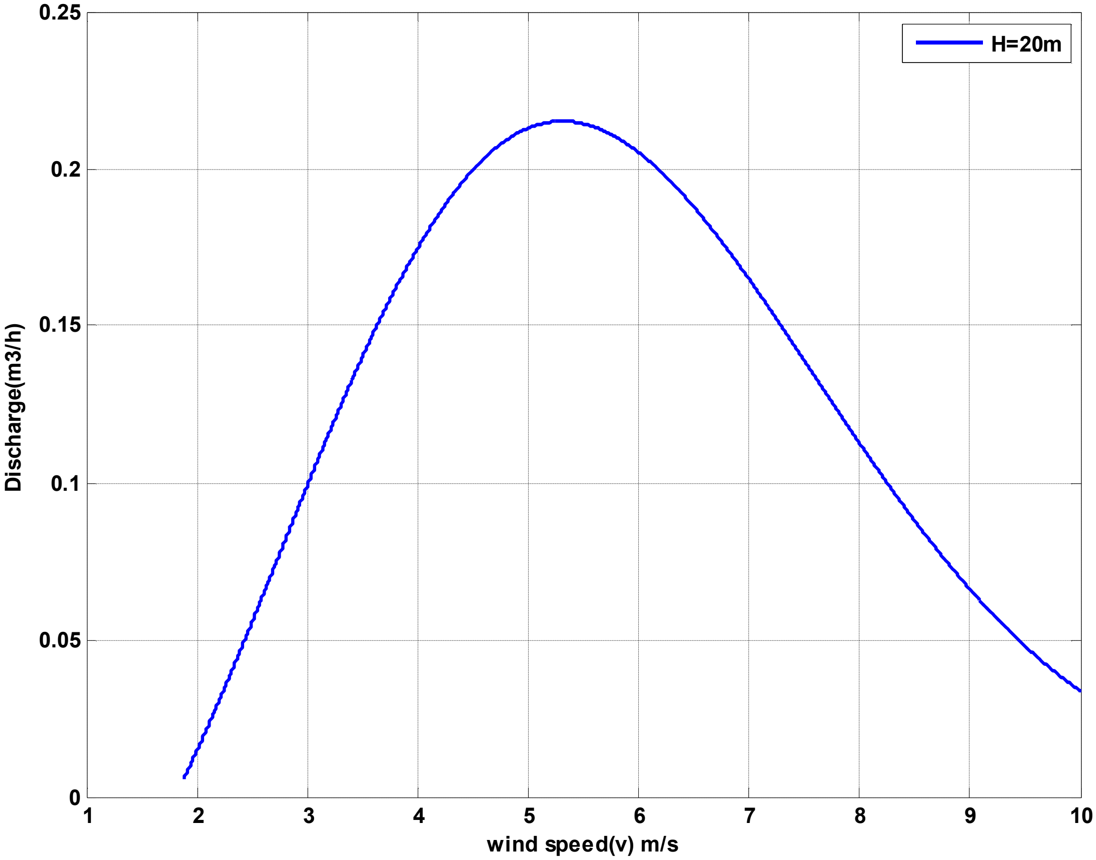


Figure 5-9: Expected discharge rate for the design month of Mekele at 20m

Table 5-12: Daily expected discharge at different pumping head for Mekele

Month	Shape parameter(k)	Scale parameter(c)	Discharge(m^3)	
			H=20m,D=3m	H=30m,D=3.5m
Jan	2.18	5.25	26.4	25.2
Feb	2.20	6.63	30.96	28.08
Mar	2.19	6.89	31.2	28.32
Apri	2.18	7.19	30.96	28.08
Oct	2.17	6.25	30.24	27.36
Nove	2.2	7.16	31.2	28.32
Dec	2.17	7.15	30.96	28.08

5.10 Monthly Irrigation Discharge for Jijiga

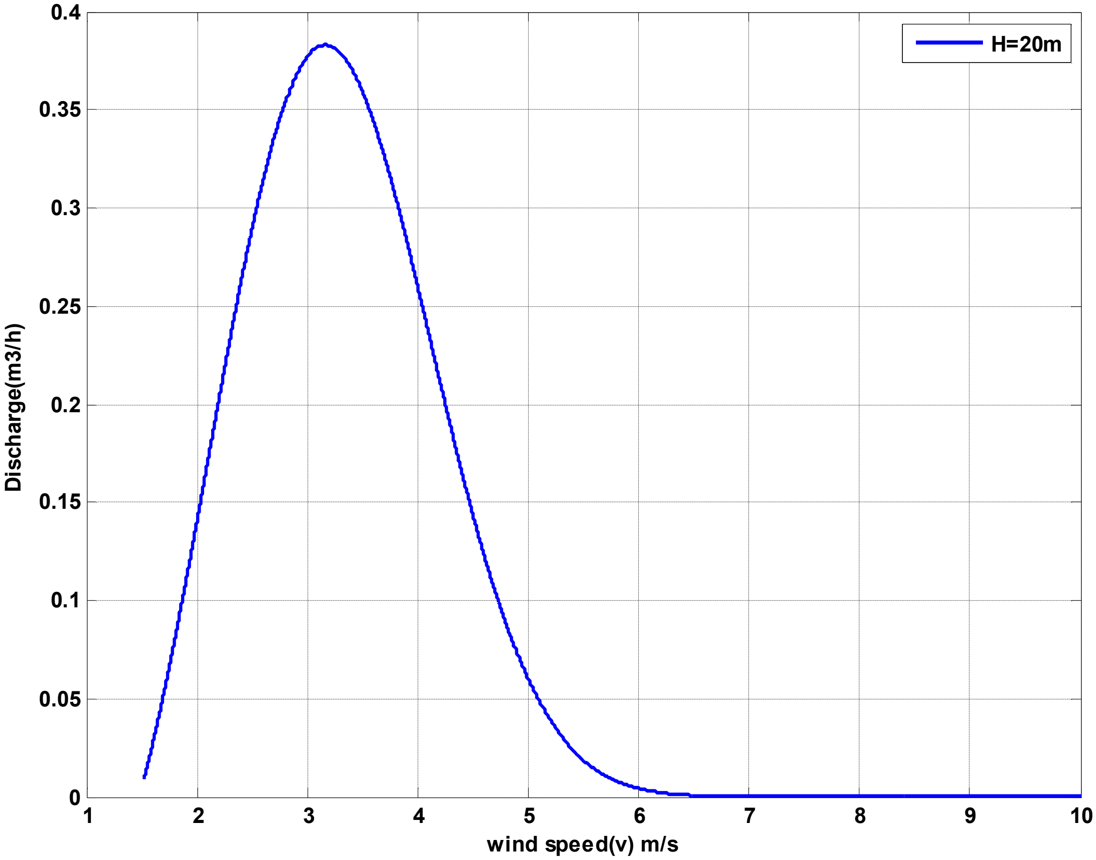


Figure 5-10: Expected discharge rate for the design month of Jijiga at 20m

Table 5-13: Daily expected discharge at different pumping head for Jijiga

Month	Shape parameter(k)	Scale parameter(c)	Discharge(m^3)	
			H=20m,D=4.5m	H=30m,D=5.5m
Jan	2.92	5.05	43.44	43.44
Feb	2.91	3.82	29.76	29.76
Mar	2.93	3.25	26.4	26.16
Apri	2.91	3.52	26.4	26.4
Oct	2.92	2.96	25.03	25
Nove	2.94	3.86	30.48	30.24
Dec	2.89	3.63	27.84	27.6

5.11 Storage Sizing for Water Supply and Irrigation

In water supply systems for human consumption, storage tanks are usually used, even in combination with engine-driven pumps. Figure 5-11 is used for storage sizing based on economic optimization of a wind pump system, once the specific costs of wind pump and storage tank are known. For relatively cheap windmill and expensive storage tank low wind pump exploitation factor is used and for expensive wind pump and cheap storage tank relatively high wind pump exploitation factor is used. In this work average wind pump exploitation factor is used for storage sizing.

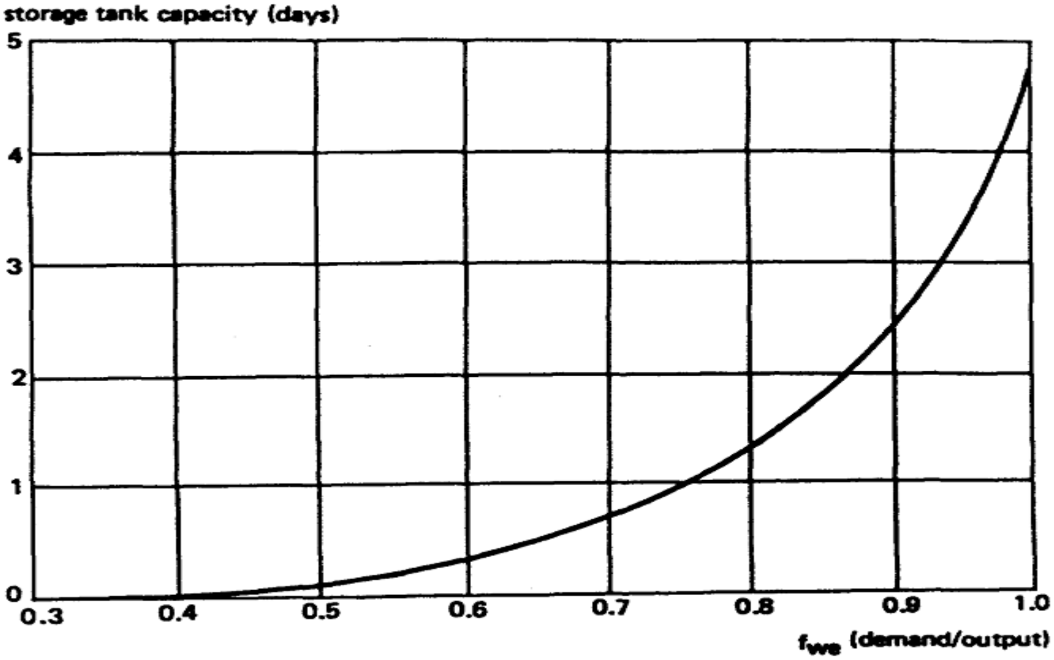


Figure 5-11: The relationship between required storage tank capacity (in days) and the wind pump exploitation factor (f_{ew})(demand/output).(source: World Bank manual)

Table 5-14: Storage tank sizing summery

Sites	Exploitation factor(f_{ew})		Storage size(m^3)	
	Water supply	Irrigation	Water supply	Irrigation
Jijiga	0.67	0.83	10	25
Assosa	0.52	0.63	10	25
Mekele	0.52	0.83	10	25

CHAPTER 6

6. Economic Analysis

In this chapter economics of wind pumping system and comparative analysis on the costs of wind pumping with that of the alternative pumping system (Diesel or petrol) will be done. Economic analysis plays a central role in any customer's decision to use wind pumping or Diesel/petrol pumping for water supply system after the technical feasibility is known.

6.1 Capital and Recurrent Cost

Costs are basically divided into investment costs (or capital costs) and recurrent costs. The investment is a cost incurred once in the lifetime of an installation (although payment of terms and interest may be spread over a longer period). Recurrent costs occur every year in more or less the same way. They include operation, maintenance and repair costs.

In order to make investment and recurrent costs comparable, one may adopt two approaches:

Annuity Method. Convert the investment into an equivalent yearly cost called the annuity. This is the amount of money that would have to be paid every year during the (economic) lifetime of the installation, if the investment were financed through a loan. The annuity is constant throughout the years, exactly covering repayment of the investment and interest on the debt. The total yearly cost is then obtained by adding the annuity and the recurrent costs together.

Present Worth Method. Convert the recurrent costs into an equivalent capital, the present worth. The present worth of future costs is the amount of capital that should be reserved at the moment of investment in order to cover all future costs.

The total life cycle cost is then obtained by adding the investment cost and the present worth of the recurrent costs together.

It must be emphasized that no economic or financial evaluation is complete without a sensitivity analysis. The assumptions on which an evaluation is based are often subject to a large margin of uncertainty. After arriving at a certain figure as the result of an economic or financial evaluation, one must also indicate how the figures obtained would change if the assumptions were varied within a reasonable range, for instance if interest rates rose at a faster rate than expected, or if the costs of operation and maintenance and other recurrent costs increased more than anticipated. In this paper present worth method is followed, as it is mostly accurate.

6.2 Life Cycle Cost Analysis.

Life cycle cost (LCC) analysis constitutes an economics tool to aid in making investment decisions. The LCC approach is particularly important when it comes to renewable energy projects which in most cases scare investors in terms of high initial costs. The conventional option, often based on a fossil fuel, appears cheaper due to low initial investment costs but the operating costs usually higher than renewable options over the project life.

The notions of present worth (PW) and future worth (FW) underpin the analysis. PW is defined as the equivalent sum of money at today’s value for money available at a point in time in the future [7]. FW, on the other hand, is described as the equivalent sum of money at a point in time in the future for money received or expended today [7].

Two factors affect the value of money over time: the inflation rate and the discount rate. Inflation rate, i, is used to compute the decrease of money value in the future. Discount rate, d, or rate of return is a measure of the amount of interest that can be earned on the amount of money that has been invested or saved. Thus, PW and FW are obtained from

$$PW = \frac{FW}{(1+d)^n} \qquad 6.1$$

$$FW = PW * (1+i)^n \qquad 6.2$$

Where:

n = time period (years)

d = discount rate (% per annum)

i = inflation rate (% per annum)

The life cycle cost (LCC) can then be obtained by adding up the Present worth (PW) of all expenditure, present and future. The LCC may include capital expenditure, operating costs, component replacement costs as well as maintenance. Here the LCC analysis will be particularly useful since it allows the cost of wind pumping to be compared with that of Diesel water pumping. In doing so, the future purchase prices of components that have to be replaced and their present values need to be calculated.

6.3 Unit Water Cost and Energy Cost

The first component of pumping costs is the capital cost, or cost of investment. This cost is incurred once in the lifetime of a pumping installation. In order to make the recurrent costs (which occur every year) comparable with the investment cost, the recurrent costs must be converted into present value.

LCC=Capital cost +Present worth of maintenance, Operating and Replacement cost

Hence levelized annual cost and unit water cost can be calculated as

$$LAC = LCC * (1+d)^n * (\frac{d}{(1+d)^n - 1}) \qquad 6.3$$

$$UWC = \frac{LAC}{Total\ Volume\ pumped(m^3)} \qquad 6.4$$

$$EC = \frac{LAC}{Hydraulic\ Load(m^4)} \qquad 6.5$$

Where:

n = project life time (years)

d = discount rate or rate of return (% per annum)

LAC = Levelised annual cost (Birr)

UWC = Unit water cost (Birr/m3)

EC = Energy cost (Birr/m^4)

EC is an indication of how different technologies rate with each other, since it levelises the influence of dynamic head; whereas UWC is a measure of the true cost of water pumped.

6.4 Cost Analysis Model

Cost analysis model is prepared using excel spreadsheets, where the inputs and outputs are shown in the model flow chart below. Based on the hydraulic load selected (head and flow rate) system sizing, component cost estimation, life cycle cost, breakeven and unit water cost was estimated for WP and DP systems.

Due to lack of WP and DP components cost at higher hydraulic load demand, the hydraulic load is restricted to 400m^4/day. The flow chart in Figure 6.1 below gives an overview of how the costing analysis was conducted and structured in the spreadsheet. The elements displayed in the diagram are discussed in the respective sections of this report

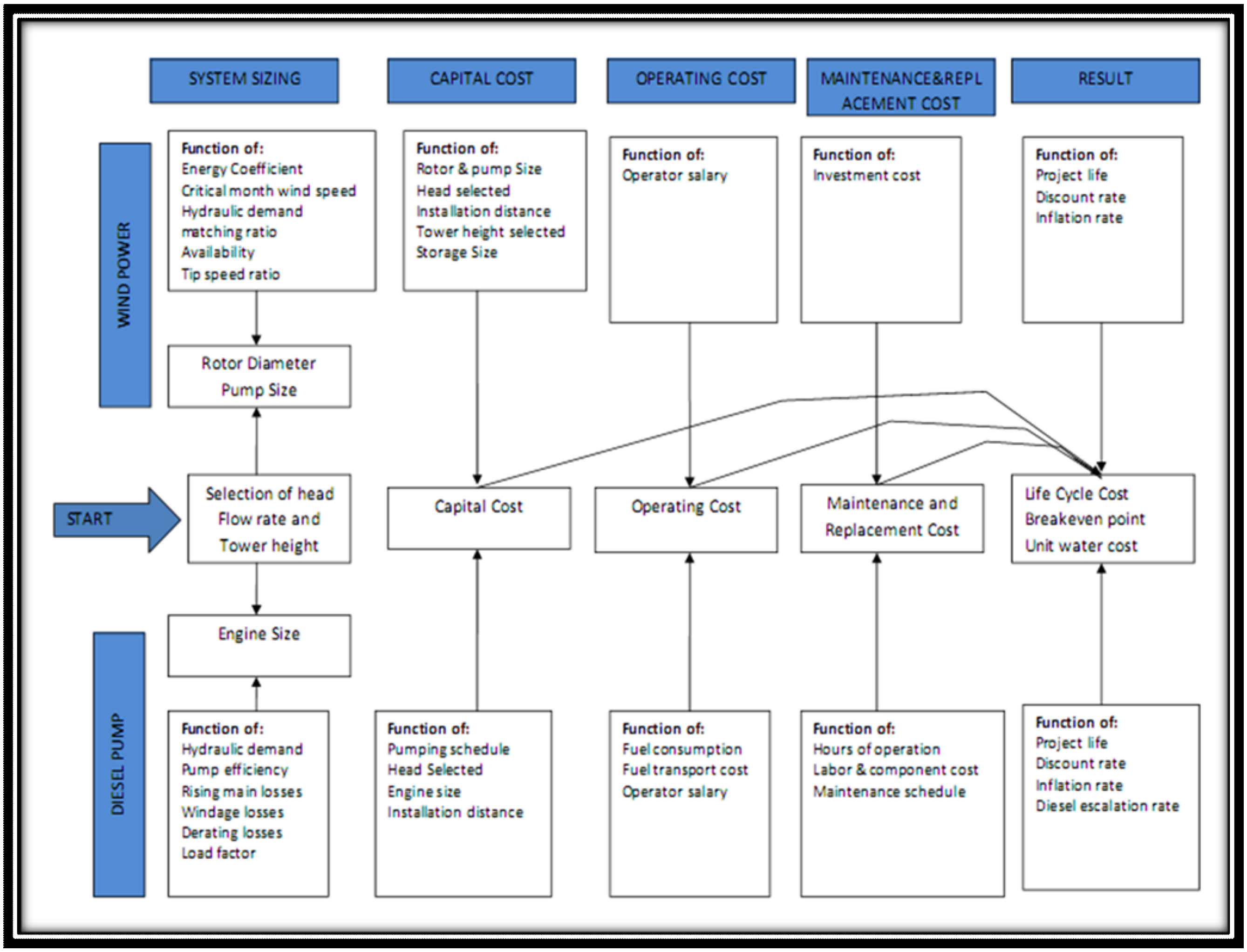


Figure 6-1: Life cycle costing model flow chart

6.4 Investment Cost Estimation of Wind Pump

Table 6-1: Cost break down of windmill components

No	***Windmill components(specifications) Φ3.6M***	***Unit price(Birr)***	***Qty***	***Total***
1	IRONMAN 702 WINDMILL/Φ3.6M	64665	1	64665
2	HEAVY STEEL 4- LEG TOWER-12M HIGH	44550	1	44550
3	WELL PUMP- Φ75MM	2794.5	1	2794.5
4	PUMP ROD FOR Φ3.6M and 6M LengthXM12	580	2	1161
5	PUMP ROD SEAL FOR Φ3.6M WIND MILL	3240	1	3240
	Sub Total for Φ3.6M			***115358***
No	***Windmill components(specifications) for Φ4.8M***	***Unit price(Birr)***	***Qty***	***Total***
1	IRONMAN 702 WINDMILL/Φ4.8M	119340	1	119340
2	HEAVY STEEL 4- LEG TOWER-12M HIGH	75870	1	75870
3	WELL PUMP- Φ75MM	2794.5	1	2794.5
4	PUMP ROD FOR Φ4.8M and 6M LengthXM12	783	2	1566
5	PUMP ROD SEAL FOR Φ4.8M WIND MILL	3240	1	3240
	Sub Total for Φ4.8M			***201361***
	Total for Φ3.6M (including fright, customs&vat)			***154623***
	Total for Φ4.8M (including fright, customs&vat)			***267458***

All Wind and Diesel pump component costs are found from manufacturers and suppliers.

Table 6-2: Cost break down of storage tank

No	*Storage tank specification*	*Size(m3)*	*Qty*	*Unit price(Birr/m3)*	*Total*
1	Concrete storage(material and labor)	10	1	1600	16000
		25	1		40000
Sub Total for water supply					16000
Sub Total for irrigation					40000

Table 6-3: Cost break down of windmill installation cost

No	*Windmill Installation cost*	*Unit price*	*Depth/Distance(m)*	*Total*
1.	10 inch Well drilling,pipe and preparation with PVC casing	3500birr/m	20,30&40	
2.	Labor and transport cost	25birr/km	1000km	25000
3.	Total Foundation cost for 10m tower	5330birr	-	5330
Sub Total for 20m depth				***100.330.00***
Sub Total for 30m depth				***135,330.00***
Sub Total for 40m depth				***170,330.00***

All installation costs are found from respective local organizations.

6.4 Operating and Maintenance Cost Estimation for Wind Pumping

Depending on the character of the maintenance and repair activities to be carried out, one may distinguish two types of maintenance and repair costs:

- A constant annual amount, more or less independent of the size of the installation, reflecting for example a regular inspection visit to each installation (monthly, yearly). This type of cost is a component of the maintenance and repair cost of most types of pumping systems.
- An annual amount proportional to the initial investment. This is the most important component of maintenance and repair costs of wind pumps. The time to be spent on maintenance and repair and the cost of spare parts is related to the size of the installation, which in its turn is related to the investment.

For Wind pumps the cost of operation is mainly related to salaries for attendance, operation of the pump, and water distribution. Assuming 5% of the investment for annual cost of Maintenance and repair (MR) and monthly salary of 200Birr for watch man/operator.

***Operating, maintenance and Repair cost*=5%Ci+2400Birr**

6.5 Investment Cost Estimation of Diesel Pump

6.5.1 Diesel Pump Capital Cost

Table 6-4: Cost break down of Diesel pump components

No	Diesel pump components(specifications)	Unit price(Birr)	Qty	Total
1	HATZ1B20DIESEL ENGINE(1.4KW)@1500RPM	22317	1	22317
2	40MMX250MM AQUA B DISCHARGE HEADX2 GROOVE	11322	1	11322
3	40MMX3.0M HEAVY TRUNCATED GALVANIZED COLUMNS	1146	7(13)	8022(14898)
4	GW0201 ORBIT ELEMENT(PUMP)	7344	1	7344
5	13MMX1410MM SHAFTS	130	12(26)	1560(3380)
6	13X40MM BOBBIN BEARINGS	240	12(26)	2880(6240)
7	40X152MM STABILIZER	336	2(4)	672(1344)
8	SET VEE BELTS	680	1	680
9	130MM PULLEY AND CENTRIFUGAL CLUTCH FITTED TO ENGINE	6702	1	6702
10	SET OF ENGINE SPARE PARTS	3164	1	3164
	Sub Total for 20m head			***64663***
	Sub Total for 40m head			***78063***
	Total for 20m head (including fright, customs and vat)			***85888***
	Total for 40m head (including fright, customs and vat)			***103686***

Table 6-5: Cost break down of storage tank

No	*Storage tank specification*	*Size(m^3)*	*Qty*	*Unit price(Birr/m3)*	*Total*
1	Concrete storage(material and labor)	10	1	1600	16000
		25	1		40000
				Sub Total for water supply	***16000***
				Sub Total for irrigation	***40000***

Table 6-6: Cost break down of Diesel pump installation cost

No	*Diesel Pump Installation cost*	*Unit price*	*Depth/Distance*	*Total*
1.	10 inch Well drilling,Pipe and preparation with PVC casing	3500Birr/m	20m,40m	70000,14000
2.	Labor and transport cost	25Birr/km	200km	5000
3.	Diesel engine foundation	5500Birr		
			Sub Total for 20m head	***80500***
			Sub Total for 40m head	***150500***
			Total investment cost for 20m head	***182388***
			Total investment cost for 40m head	***270186***

6.6 Operating Cost Estimation for Diesel Pumping

The operating costs for to the diesel pumping system includes the operator costs (person starting the diesel engine and looking after the diesel system).It is assumed to be 2400birr per annum.

The liters of diesel consumed per annum are calculated from the running time of the diesel pump and its fuel consumption. A fuel cost escalation of 2% has been assumed but the fact remains that this is a indeterminable parameter as it depends on oil reserves, conflict in oil producing countries and exchange rate. The fuel consumption for the selected minimum capacity HATZ diesel engine is 0.44 lit/hr.

The transport cost of fuel to site is added to the operating cost of the diesel pump. It is assumed that the average distance to the fuel supply infrastructure is at a 100km distance (service distance) and that 7 trips for fuel are needed per year (assuming l barrel per trip to be transported). The cost rate of the transport is set to be 4.2birr/km at current fuel prices.

6.7 Maintenance and Replacement Costs

The maintenance and replacement schedule and detail of the pumping systems applicable to diesel pumping are dependent on the technology employed. The replacement schedule is dependent on the ruggedness of the system, the operating environment (water quality, diesel quality, direct exposure to sunlight, excessive temperature etc) as well as the level of maintenance performed. Diesel pumps require minor service, major service and overhauls in regular intervals. A minor service includes oil change (topping up of oil included here) and air, fuel and oil filters. Major services include decarburization, adjustments, oil change and filter replacements and require a skilled personnel which is assumed to be in the region.

An overhaul includes the tasks of a minor and major service, replacements of parts (e.g. crankshaft) and drilling of cylinders and requires skilled personnel. The following schedule has been selected for the service and replacement intervals of high quality diesel engine.

Table 6-7: Maintenance and Replacement interval for high quality diesel engine

No.	Maintenance and Replacement	Maintenance and Replacement interval	Remark
1	Minor service	4 times per year	
2	Major service	2 times per year	
3	Overhaul	Every 8000hour	
4	Replacement	Every 20000hour	

Based on practical experiences and consulting maintenance personnel's who work in rural water supply in Oromiya region, the following maintenance cost is assumed.

Table 6-8: Maintenance cost of diesel engine

No.	Maintenance	Maintenance cost	Remark
1	Minor service	4000Birr per year	
2	Major service	10000Birr per year	
3	Overhaul	20000 Birr Every 4 year	6hour running per day

The minor service is done locally and no transport costs have been added. The major service is done by professional services on site. The overhaul of a diesel engine is done in the workshop and thus requires professional services as well as services trips. The replacement of an engine is determined by its condition (either overhaul or replace) and this is usually assessed in the workshop. Transport costs for overhaul and replacement are therefore doubled to reflect two trips to site.

The transport costs for major service, overhaul and replacement are based on the distance to the fuel supply infrastructure (assumed as 100km)

6.7 Financial Parameters

The life cycle costing performed here uses real discount rate, which consider inflation rate. The project life time is 20year. National Bank Nominal discount rate and inflation rate is taken as 12% and 5% respectively. The real discount rate can be corrected using the relation below:

Real discount rate= ((1 + nominal discount rate)/ (1 + inflation rate) - 1)

Hence real discount rate is 6.7%.

6.8 Life Cycle Cost Analysis Result for Water Supply

Based on the investment and recurrent costs, the unit water pumping cost, energy cost and life cycle cost breakeven point for both pumping technologies is done at different total pumping head.

Table 6-9: Wind and Diesel water supply cost analysis summery

No.	Cost	Total head(H)			Total head(H)		
		Diesel pumping			Wind pumping		
		H=20m	H=40m	H=60m	H=20m(D=3.6m)	H=40m(D=4.8m)	H=60m(D=6m)
1	Life cycle cost(Birr)	1,016,302	1,158,558	1,300,814	417,252	742,585	1,222,415
2	Unit Water Cost for Assosa(Birr/m^3)	25.10	29.19	32.77	7.01	12.48	20.07
	Unit water cost for Mekele(Birr/m^3)				5.66	10.08	16.06
	Unit water cost for Jijiga(Birr/m^3)				6.71	11.94	18.74
3	Energy Cost(Birr/m^4)	1.28	0.73	0.55	0.53	0.43	0.51
4	Break even occurs after(year)	2	5.4	16.7	2	5.4	16.7

6.8.1 Life Cycle Cost Comparison for Wind and Diesel Pumping

The life cycle cost of diesel and wind pumping options in the summary table, shows the true cost incurred over the project lifetime for the same service rendered (water delivered over a fixed head within a fixed period). Since the LCC varies with daily flow rate and head, for constant flow rate, three total heads have been selected and shown in the Figure below.

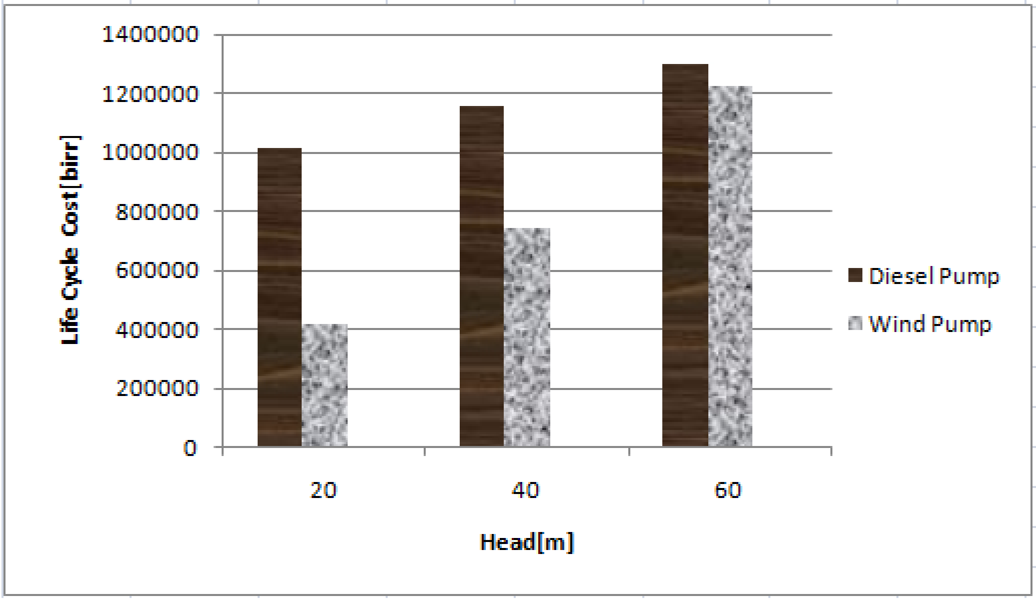


Figure 6-2: Life cycle cost for WP and DP

It can be seen that the LCC of the WP increase with increasing hydraulic load, as the investment cost increases very significantly. Whereas, the LCC of the DP systems remain fairly flat at lower hydraulic load as compared to WP.Whereas for 60m head we can see that the life cycle cost for both systems gets fairly equal. A diesel pump is not efficient at such low power requirements and the fuel consumption remains more or less fixed at the minimum rate of 0.44litres/hour.

6.8.2 Unit Water Cost Comparison for Wind and Diesel Pumping

The UW costs give an indication of the actual cost of water pumping using either of the diesel or wind system.

The UWC cost for WP is lower than that of DP for both delivery heads as shown for mekele case.UWC for both systems increases proportionally. This is because of delivery head increase, hence investment cost also increases. The higher UWC for DP is due to high maintenance and replacement costs incurred throughout the 20years life time.

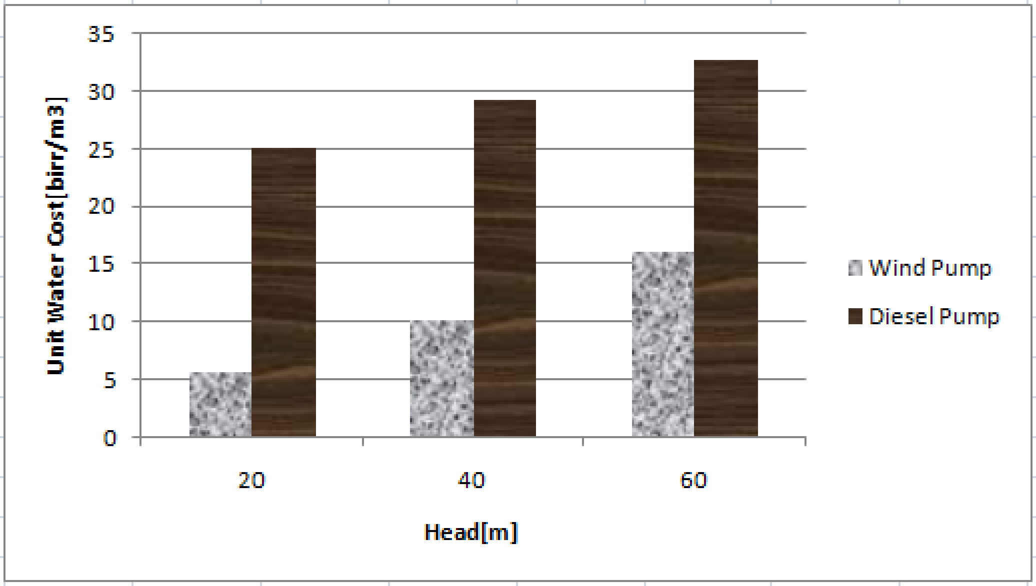


Figure 6-3: Unit water cost for WP and DP at mekele

6.8.3 Energy Cost Comparison for Wind and Diesel Pumping

The energy cost for both systems decreases as the delivery head increase. The respond from DP system is very significant than WP. And it also an indication of how the two different technologies rate with each other

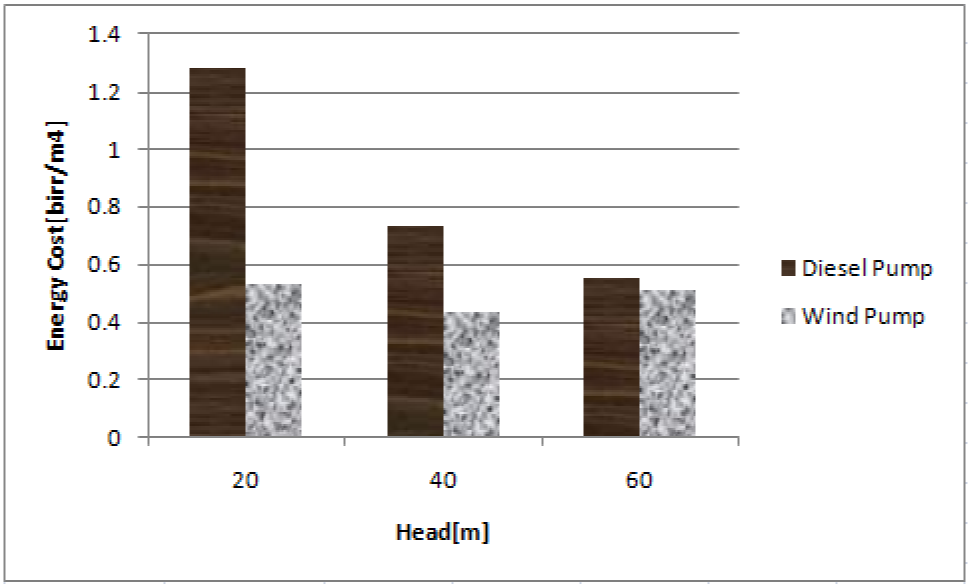


Figure 6-4: Energy cost for WP and DP

6.8.4 Breakeven for Wind and Diesel Pumping

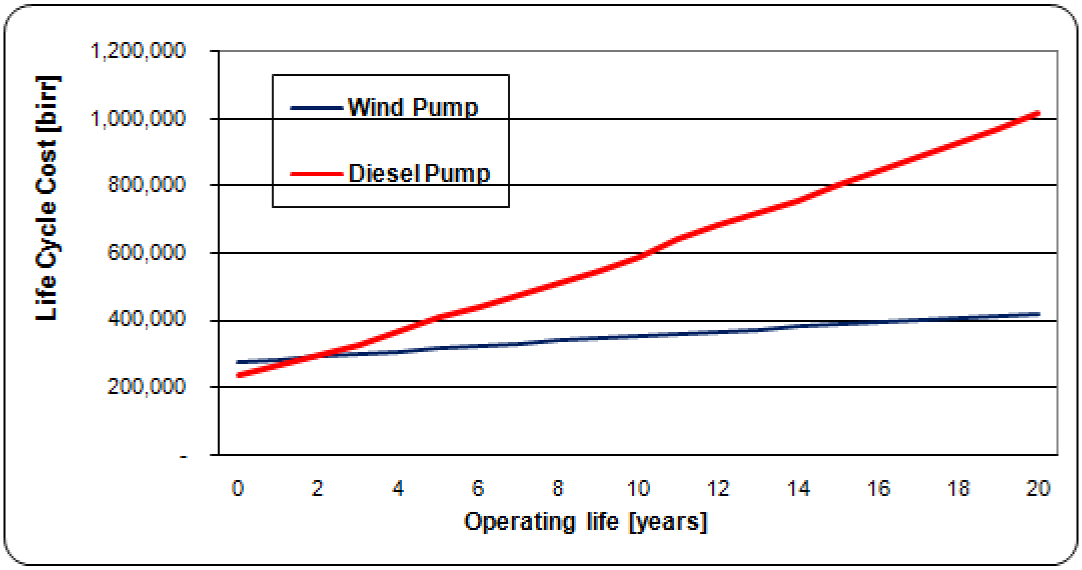


Figure 6-5: Breakeven point for WP and DP systems

The choice between WP and DP technology should be made based on comparative life cycle costing where the solution with a lower cost over the project life is selected. An indicator of attractiveness is the years to breakeven, which is when the cumulative LCC of WP becomes lower than the cumulative LCC of DP. The shorter the years to breakeven, the more attractive the wind pump solution becomes and the higher the cost savings over the project life. As seen in Fig above for 20m head, breakeven occurs early 2 years after letting the system in to operation. This makes WP very attractive over DP technology.

6.8.5 Sensitivity Analysis on LCC and Breakeven Point

The sensitivity analyses for financial parameters variation are shown in Figure below. As expected the LCC of the DP is highly sensitive to variation in financial parameters as compared to WP, hence the Unit water cost. The Breakeven point of the two systems is almost the same (slightly affected) for 20m head and it shows a decrease to 5.1 year for 40m head, this is due to most of the costs associated with diesel pumping system are the future cost components which are therefore more affected by the fuel and maintenance costs.

Table 6-10: Wind and Diesel water supply cost analysis summery

No.	Cost	Total head(H)		Total head(H)	
		Diesel pumping		Wind pumping	
		5% Inflation	8% Inflation	5% Inflation	8% Inflation
		H=20m	H=20m	H=20m(D=3.6m)	H=20m(D=3.6m)
1	Life cycle cost(Birr)	1,016,302	1,286,150	417,252	537,018
2	Unit Water Cost for Assosa(Birr/m^3)	25.10	25.25	7.01	7.04
	Unit water cost for Mekele(Birr/m^3)			5.66	5.68
	Unit water cost for Jijiga(Birr/m^3)			6.71	6.73
3	Energy Cost(Birr/m^4)	1.28	1.26	0.53	0.52
4	Break even occurs after(year)	2		5.4	5.1

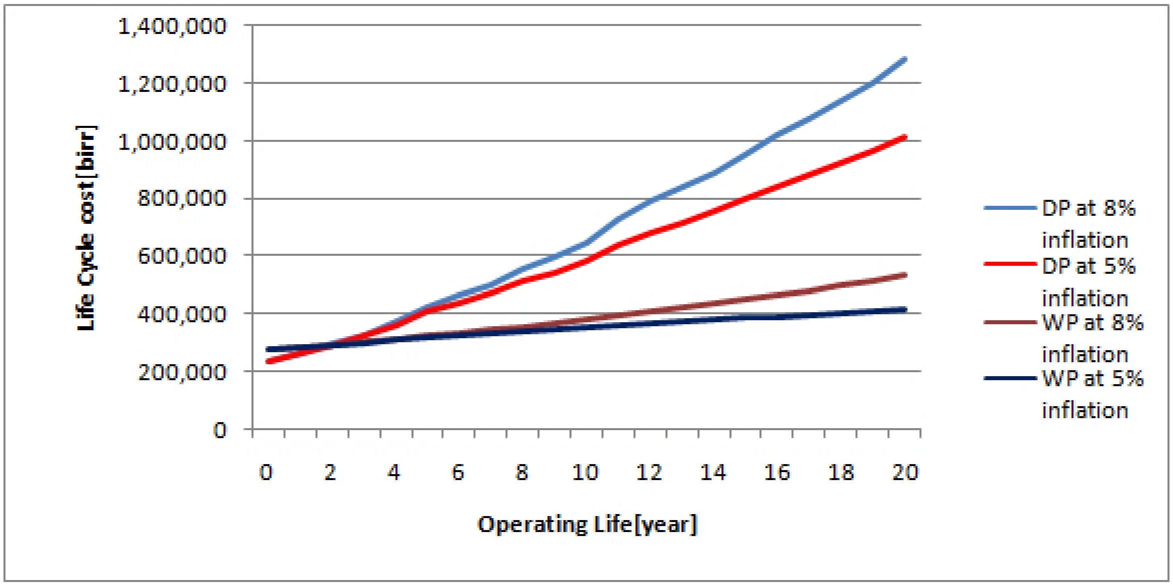


Figure 6-6: Breakeven point sensitivity for WP and DP systems

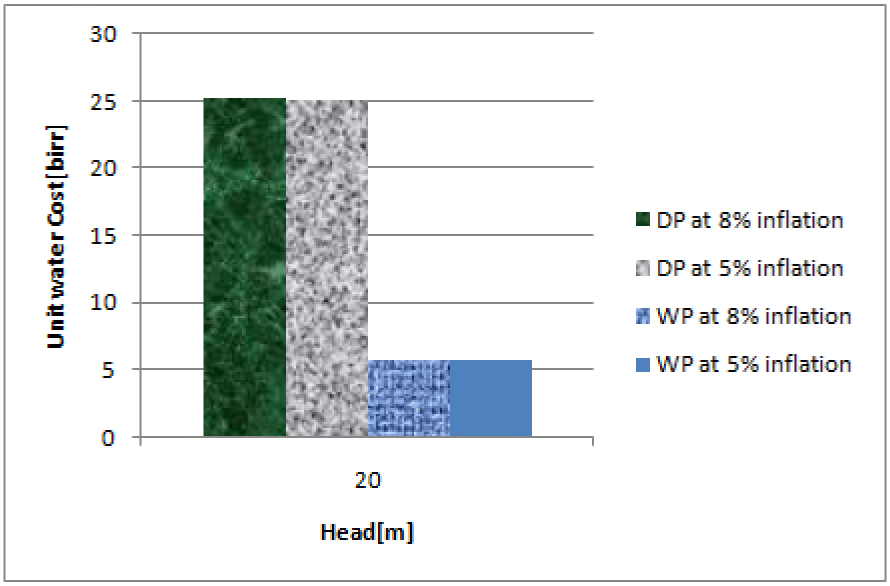


Figure 6-7: Unit water cost sensitivity for WP and DP systems

6.9 Life Cycle Cost Analysis Result for Irrigation

Based on the investment and recurrent costs, the unit water pumping cost, energy cost and life cycle cost breakeven point for both pumping technologies is done at different total pumping head.

Table 6-11: Wind and Diesel water supply cost analysis summery

No.	Cost	Total head(H)		Total head(H)	
		Diesel pumping		Wind pumping	
		H=20m	H=30m	H=20m(D=3.6m)	H=30m(D=3.6m)
1	Life cycle cost(Birr)	1,016,302.00	1,133,667	467,901.00	671,699
2	Unit Water Cost mekele(Birr/m^3)	10.24	11.43	6.70	9.63
3	Break even occurs after(year)	3.4	3.4	5.8	5.8

Here, WP life cycle cost at 20 and 30m head for assosa and jijiga is found higher than DP life cycle cost for the respective heads. Hence break even for DP over WP occurs during project initial period.

6.9.1 Life Cycle Cost Comparison for Wind and Diesel Pumping

The life cycle cost of diesel and wind pumping options in the summary table, shows the true cost incurred over the project lifetime for the same service rendered (water delivered over a fixed head within a fixed period). Since the LCC varies with daily flow rate and head, for constant flow rate, two delivery heads have been selected and shown in the Figure 6.8 below.

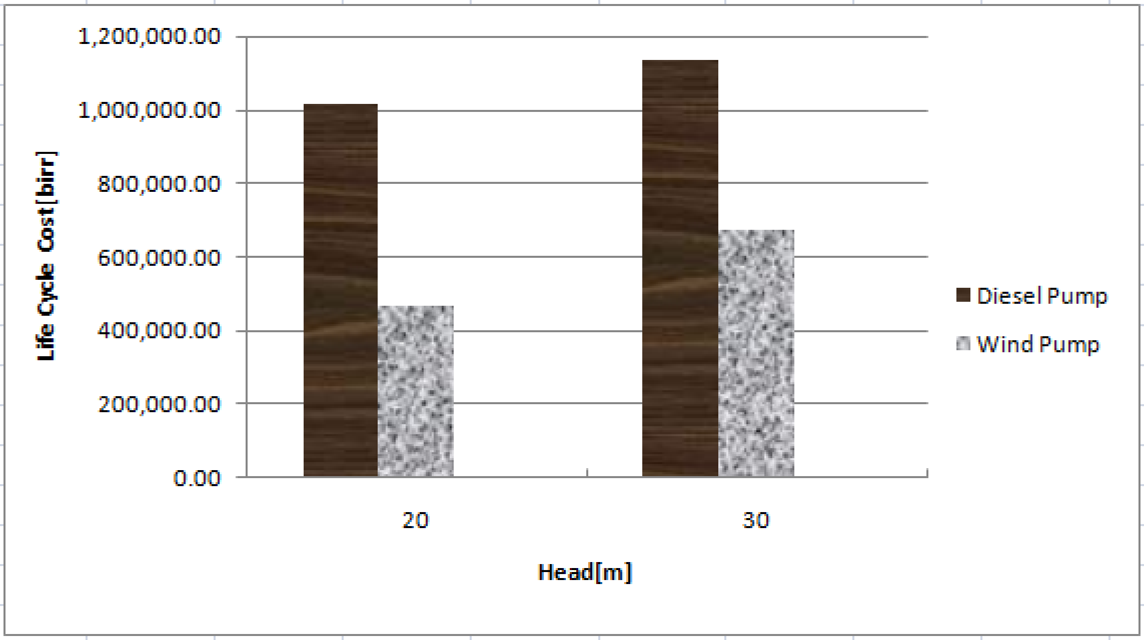


Figure 6-8: Life cycle cost for WP and DP

It can be seen that the LCC of the WP increase with increasing hydraulic load, as the investment cost increases very significantly. Whereas, the LCC of the DP systems remain fairly flat at lower hydraulic load as compared to WP. A diesel pump is not efficient at such low power requirements and the fuel consumption remains more or less fixed at the minimum rate of 0.44litres/hour.

6.9.2 Unit Water Cost Comparison for Wind and Diesel Pumping

The UW costs give an indication of the actual cost of water pumping using either of the diesel or wind system.

The UWC cost for WP is lower than that of DP for both delivery heads.UWC for both systems increases proportionally. This is because of delivery head increase, hence investment cost also increases. The higher UWC for DP is due to high maintenance and replacement costs incurred throughout the 20years life time.

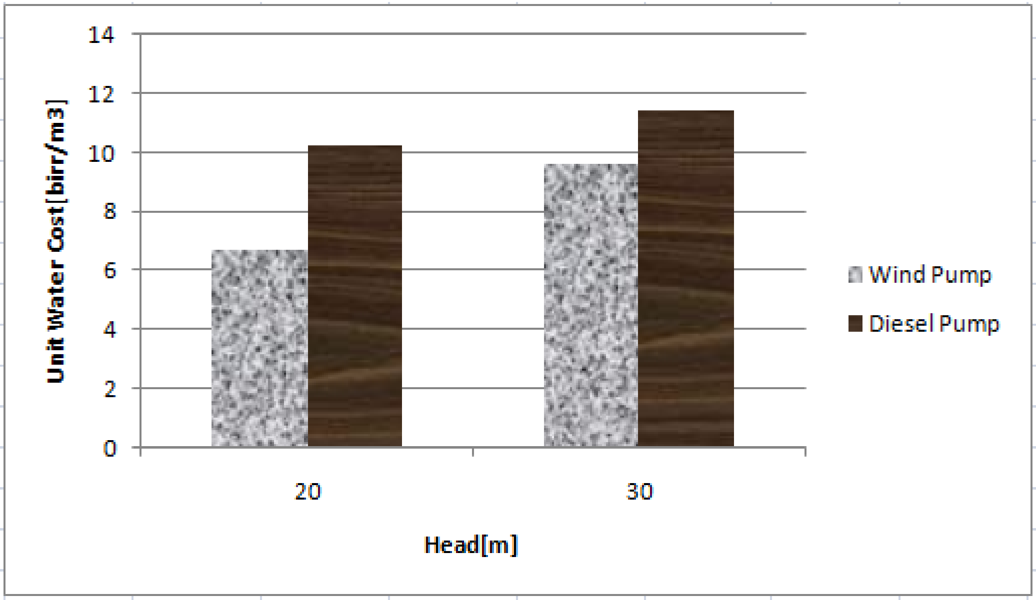


Figure 6-9: Unit water cost for WP and DP

6.9.3 Breakeven for Wind and Diesel Pumping

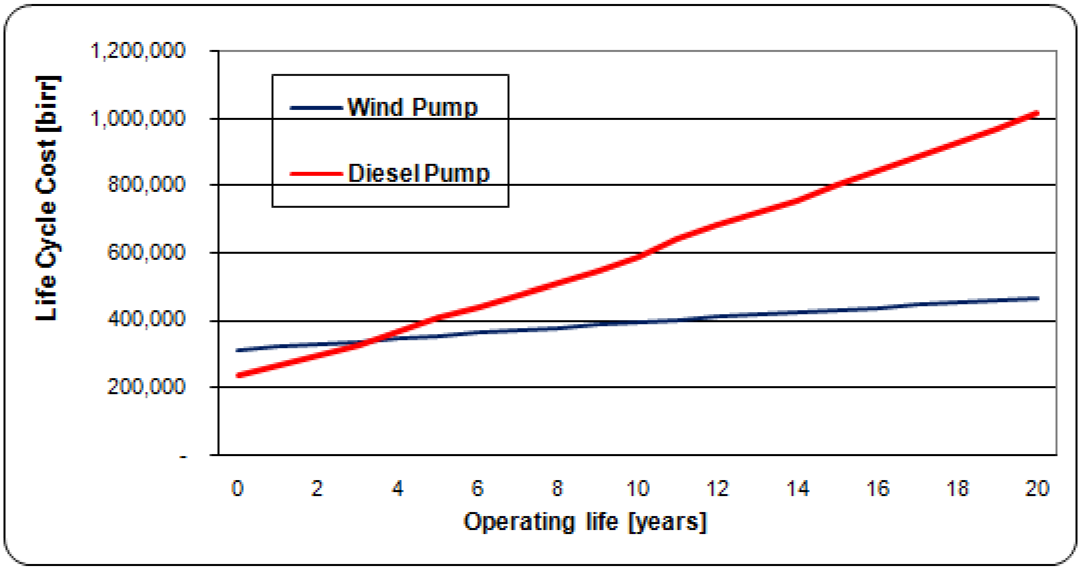


Figure 6-10: Breakeven point for WP and DP systems

The choice between WP and DP technology should be made based on comparative life cycle costing where the solution with a lower cost over the project life is selected. An indicator of attractiveness is the years to breakeven, which is when the cumulative LCC of WP becomes lower than the cumulative LCC of DP. The shorter the years to breakeven, the more attractive the wind pump solution becomes and the higher the cost savings over the project life. As seen in Fig above for 30m head, breakeven occurs early 3 years after letting the system in to operation. This makes WP very attractive over DP technology.

As a general conclusion the results for the years-to-breakeven over a certain operating range considered for water supply taking mekele's wind data are shown in the table below.

The numbers in the cells represent the years-to-breakeven for which WP become cheaper to run than diesel pump. The dark grey fields marked "Diesel" indicate that the diesel option is to be selected.

Table 6-12: Breakeven summary for different Head and daily flow rate

		daily flow rate[m^3/day]				
		2	4	6	8	10
Head[m]	10	0.00	0.00	0.00	0.00	0.2
	20	0.00	0.00	1.50	1.70	1.9
	30	0.00	0.00	0.00	5.30	5.5
	40	0.00	0.00	4.00	4.10	5.4
	50	0.00	0.00	2.60	4.00	16.2
	60	0.00	0.00	0.20	15.20	16.7
	70	0.00	0.00	13.90	14.20	Diesel
	80	0.00	0.00	12.50	Diesel	Diesel

Using the above breakeven results, the figure below shows hydraulic load lines which are used to indicate regions where WP and DP can be cheaper with respective to each other. In this regard WP working on the lowest hydraulic load line (100m^4/day) in this region will break even in less than 0.2 year which is almost at letting of the WP operational. Similarly WP working on hydraulic load line (400m^4/day) will break even in less than 5.5

year. For Hydraulic loads between 400 and 600, break even occurs very lately, but still WP is cost effective than DP.

In general WP working under hydraulic load lines (400m^4/day) are more cost effective than DP.similarly DP working above hydraulic load lines (600m^4/day) are more cost effective than WP

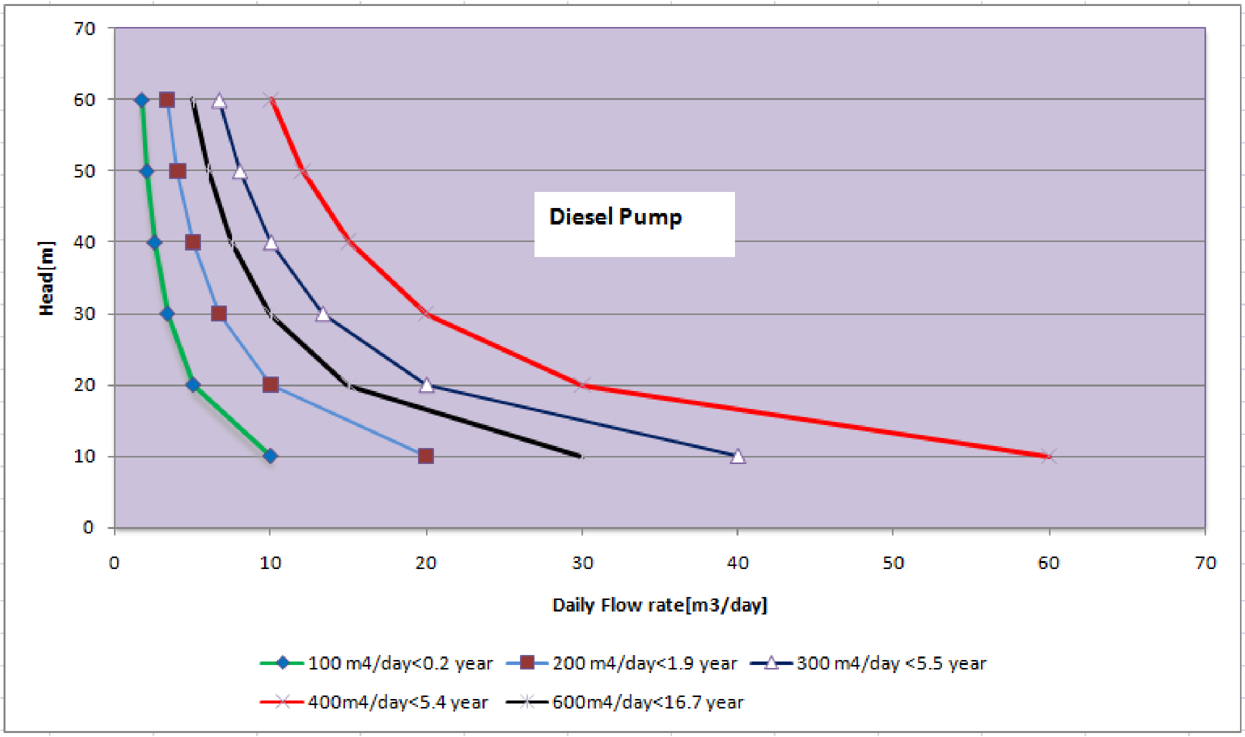


Figure 6-11: Breakeven for different Hydraulic load lines for water supply

Similarly for irrigation, the figure below shows hydraulic load lines which are used to indicate regions where WP and DP can be cheaper with respective to each other for irrigation application. In this regard WP working on the lowest hydraulic load line (500m^4/day) in this region will break even in less than 3.4 where as WP working on hydraulic load line (1000m^4/day) will break even in less than7.5 year. In general WP working under hydraulic load lines (1000m^4/day) are more cost effective than DP.where as DP working above hydraulic load lines (1000m^4/day) are more cost effective than WP for irrigation application

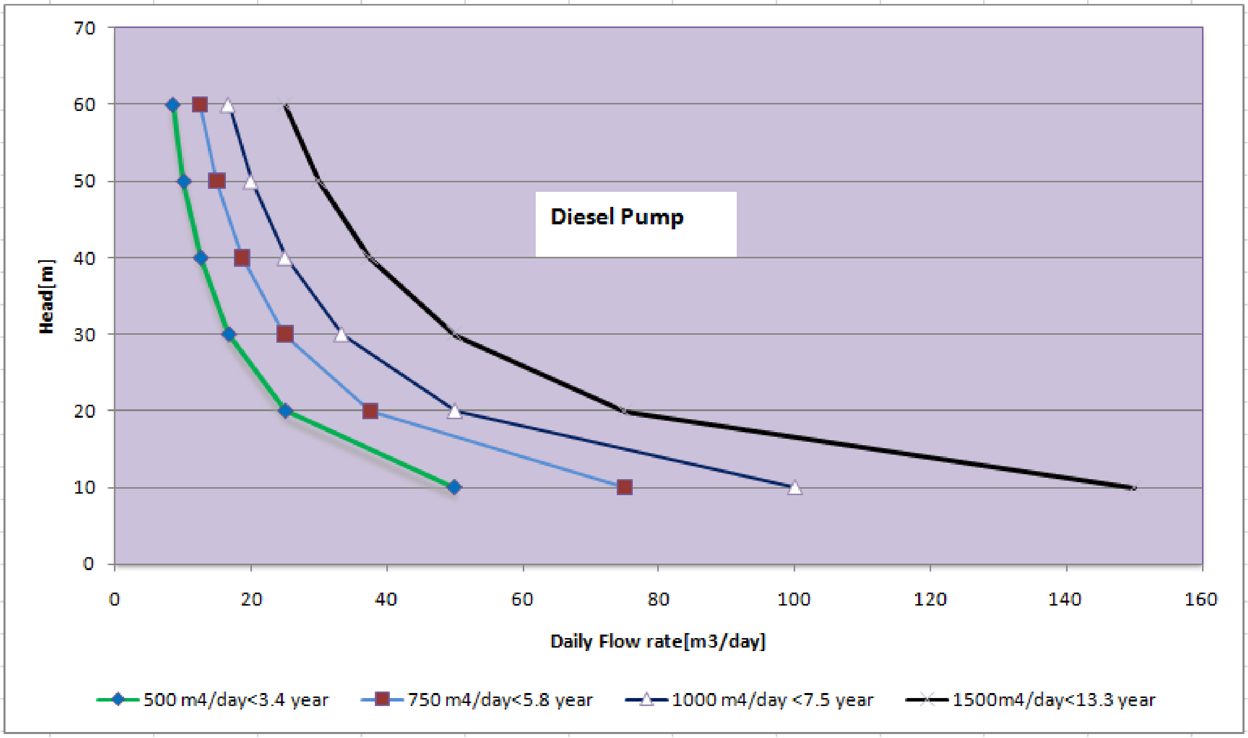


Figure 6-12: Breakeven for different Hydraulic load lines for irrigation

CHAPTER 7

7.1 Conclusion and Recommendation

An assessment of the wind resource has been done for 35 stations in Ethiopia using hourly measured data from NMSA of Ethiopia. Monthly and yearly wind distribution patterns for stations in consideration are developed using HOMER.

The result from economic feasibility of wind pumping as compared to Diesel pumping for the selected stations shows that at lower hydraulic demand for both water supply and irrigation wind pumping is better cost effective than Diesel pumping. For wind pump water supply, monthly average in the critical month above 2.5m/s for low hydraulic load is a good option over Diesel water pumping, where as for wind pump irrigation monthly average in critical month above 4m/s for low hydraulic load is a good option over Diesel water pumping.

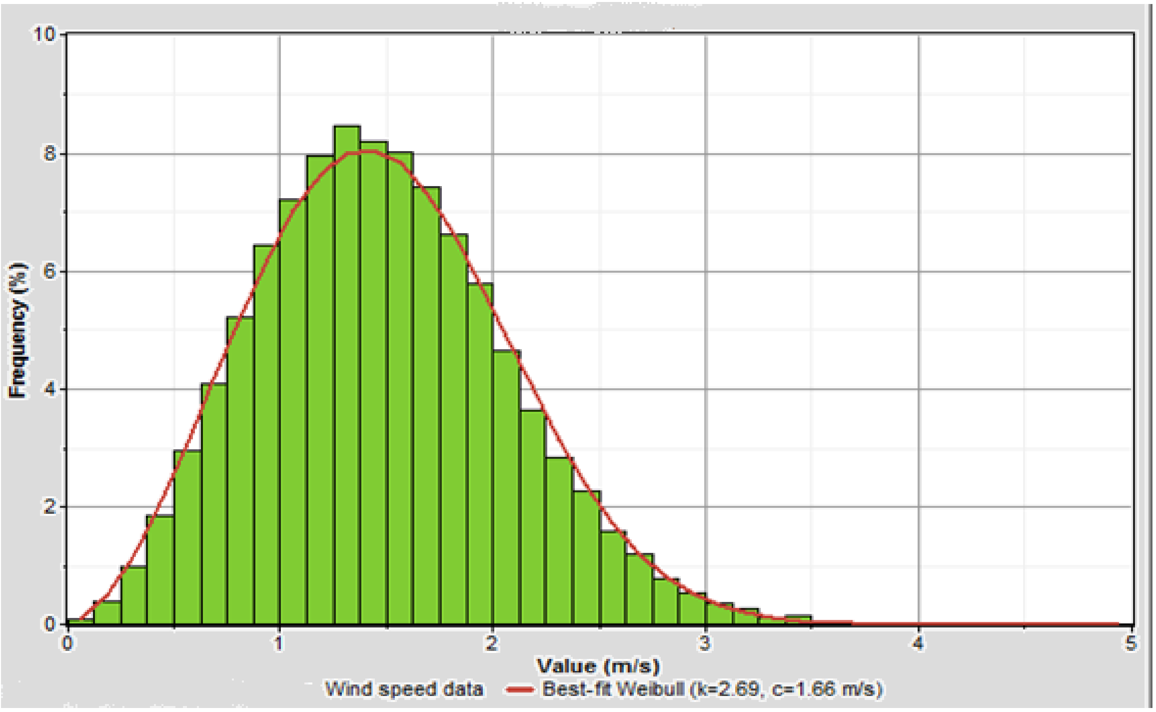
Assessment of Ethiopia's natural wind resource base indicates that the country has a huge potential that can be used for water pumping for village water supply and irrigation in addition to power generation. There are, however, formidable challenges like low purchasing power, unfavorable public attitude towards the private sector and unfair regulations that work against development and dissemination of renewable energy technologies. It is thus recommended that the government, non-governmental organizations and the public make concerted efforts to overcome these challenges by using more flexible approaches to improve the lack of clean water supply in rural areas of Ethiopia.

Since the availability of wind data in National Meteorological Services Agency (NMSA) of Ethiopia is very limited, attention should be given to make the meteorological data available in the form required for researchers of the country. More over wind measuring stations and measuring hourly intervals should be increased and decreased respectively.

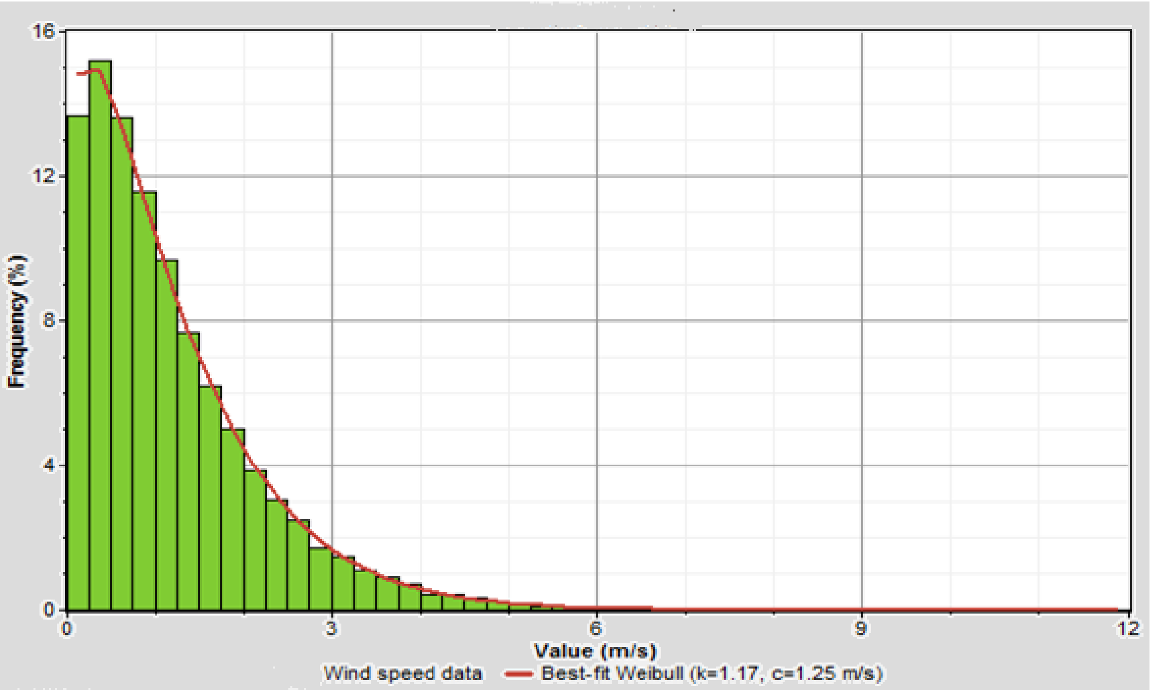
Finally, it is recommended that, to know the exact wind resource potential of Ethiopia, the density of wind measuring stations should be increased as much as possible. Moreover for wind pump sizing for village water supply and irrigation wind history of a specific location has to be taken, as the wind speed is very dependent on topography.

APPENDIXES

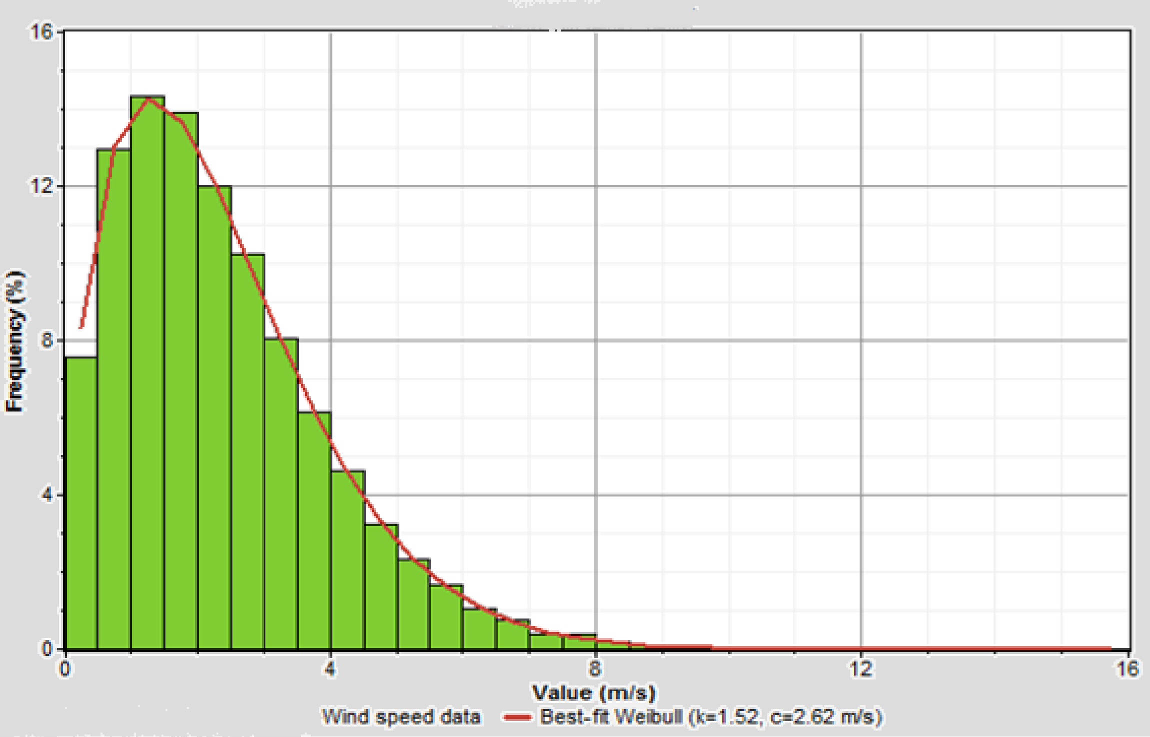
Appendix A: Annual Weibull Wind Distribution Patterns



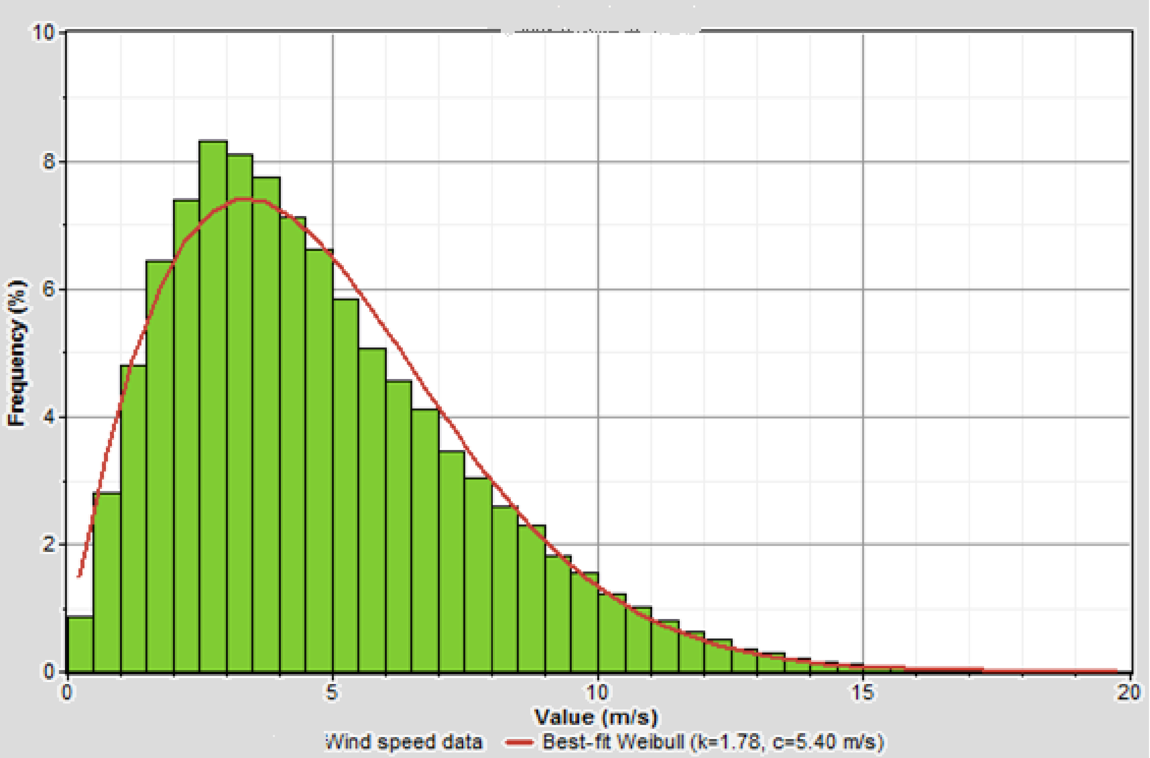
Gore annual observed and Weibull distribution



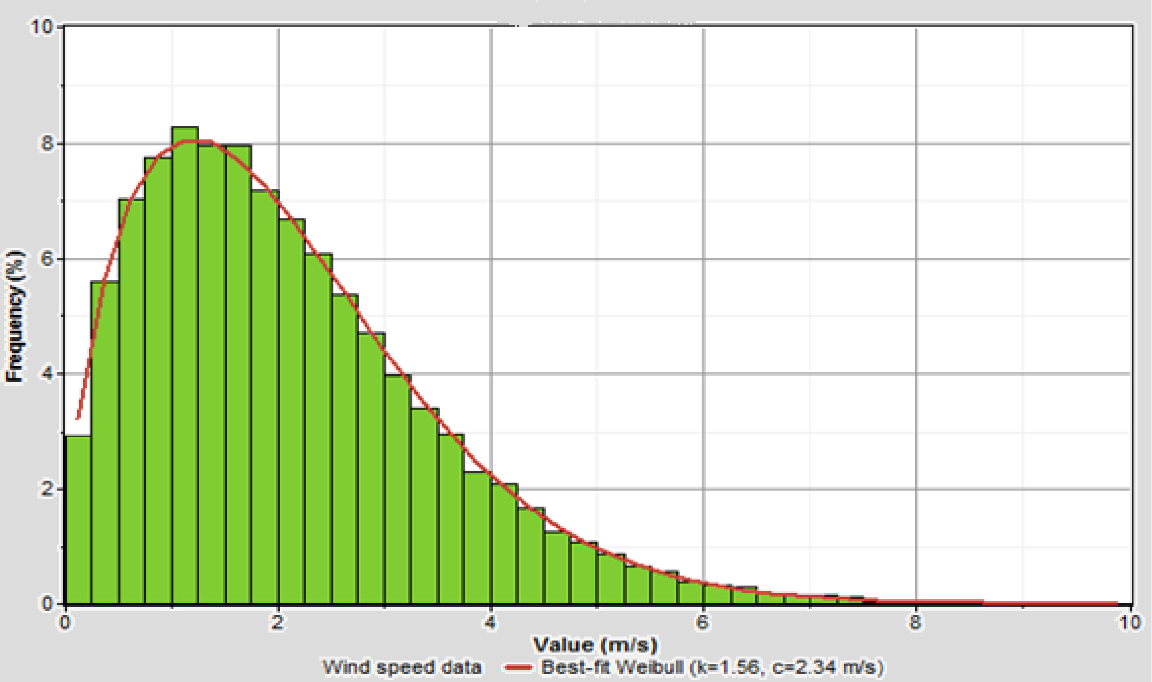
Gonder annual observed and Weibull distribution



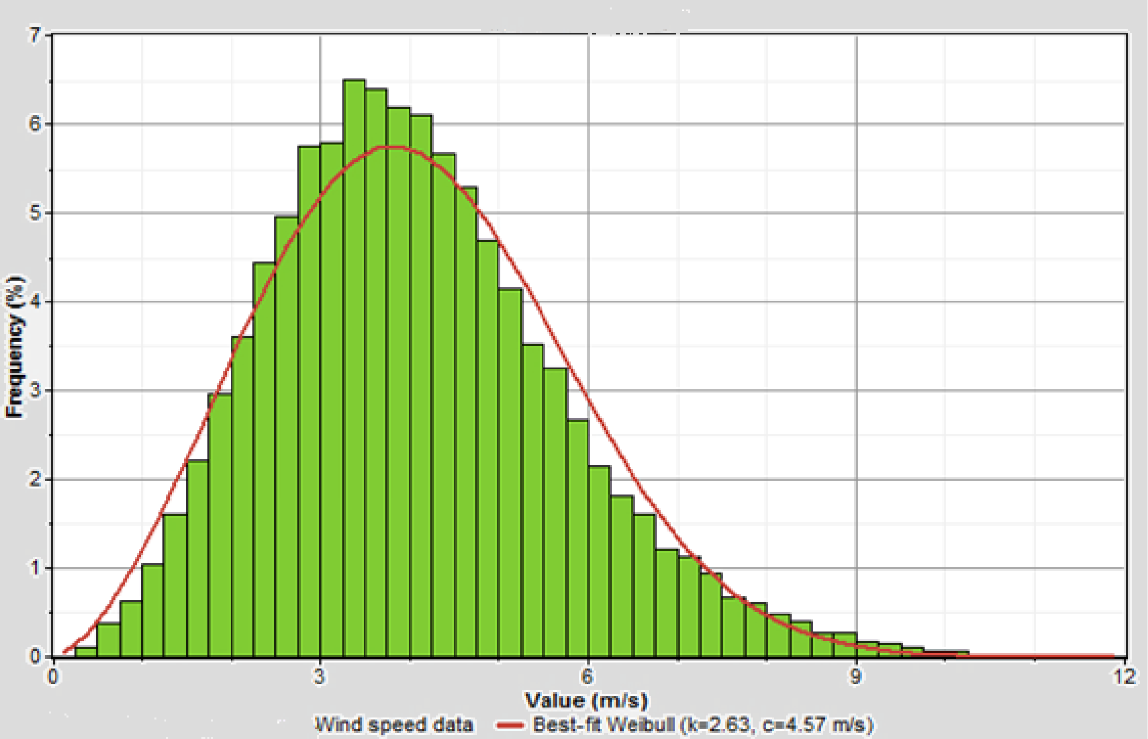
Kombolcha annual observed and Weibull distribution



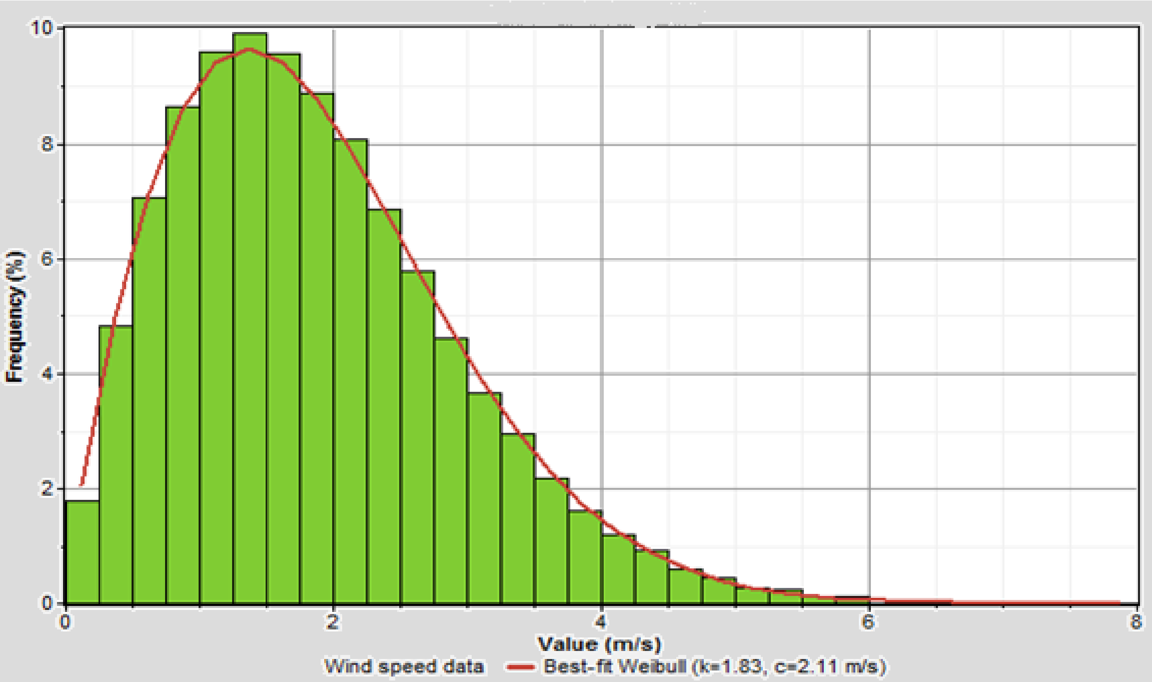
Mekele annual observed and Weibull distribution



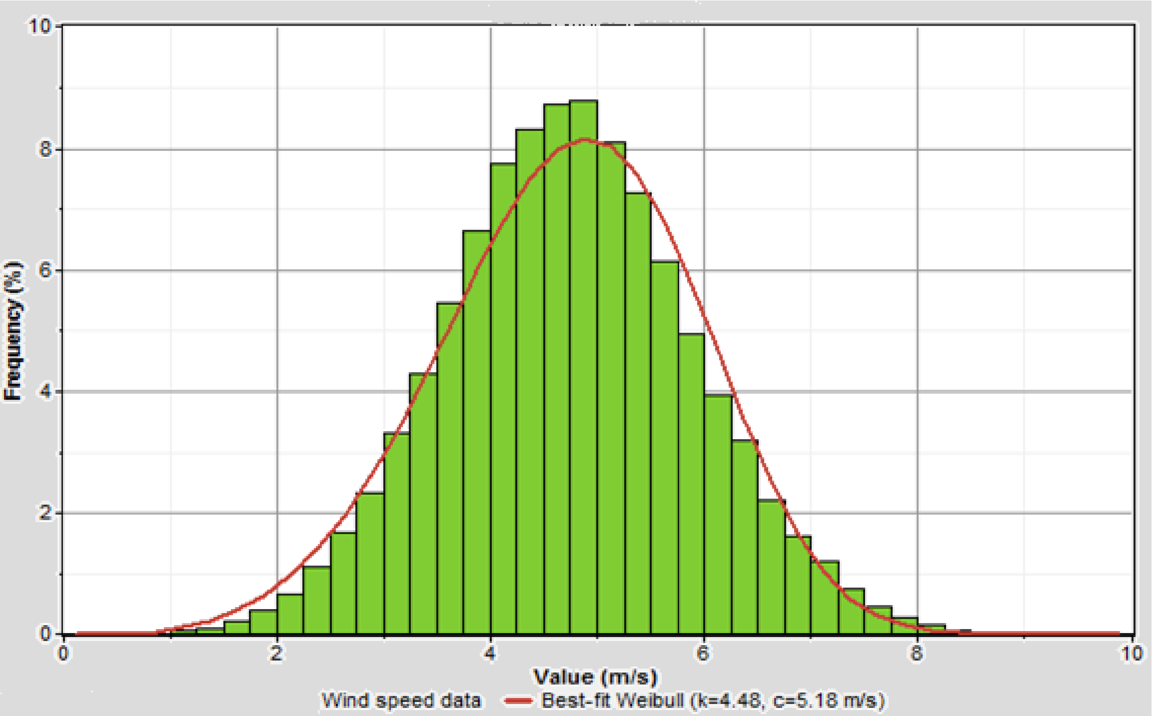
Metehara annual observed and Weibull distribution



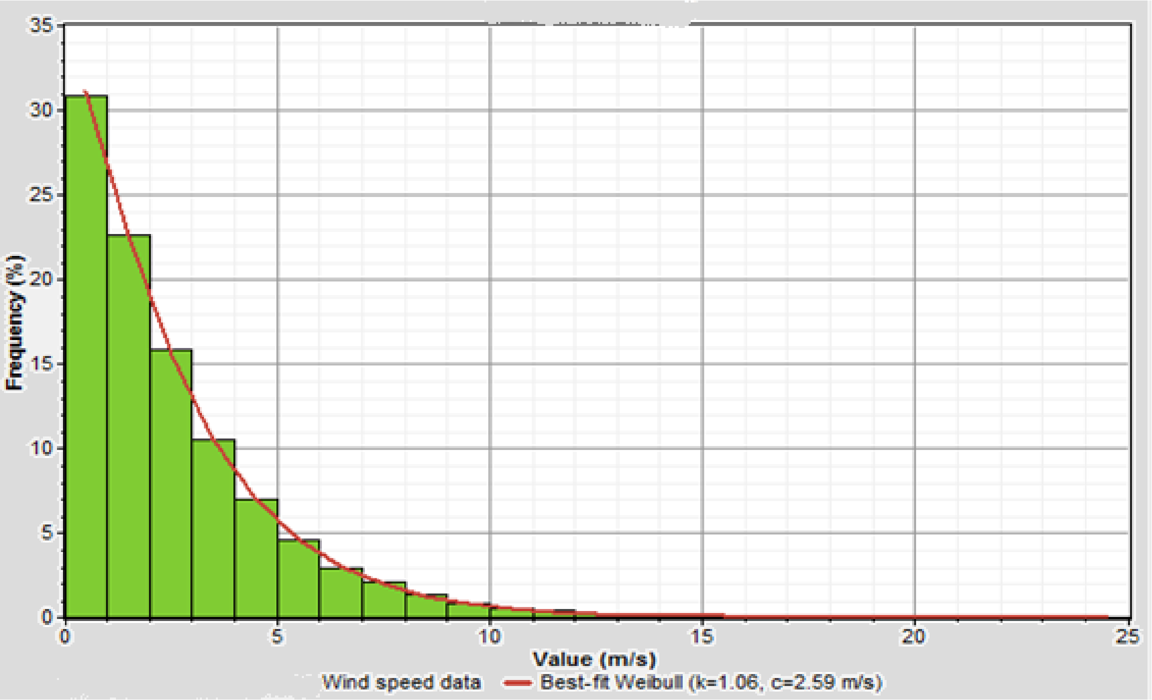
Negele annual observed and Weibull distribution



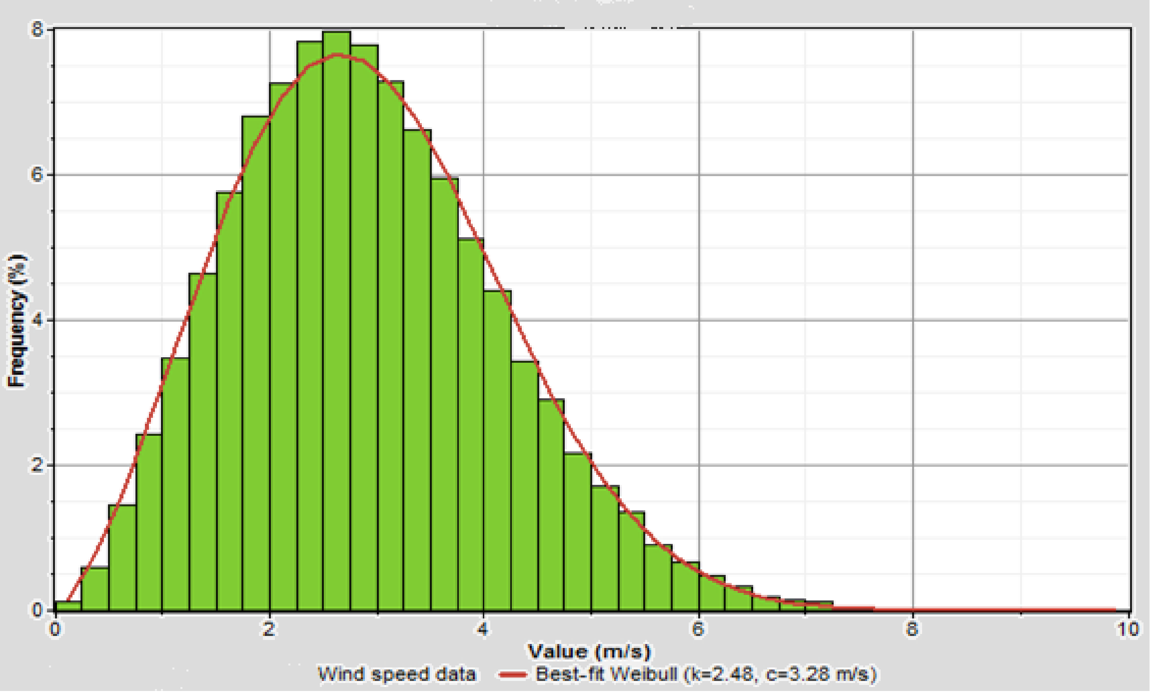
Nekemt annual observed and Weibull distribution



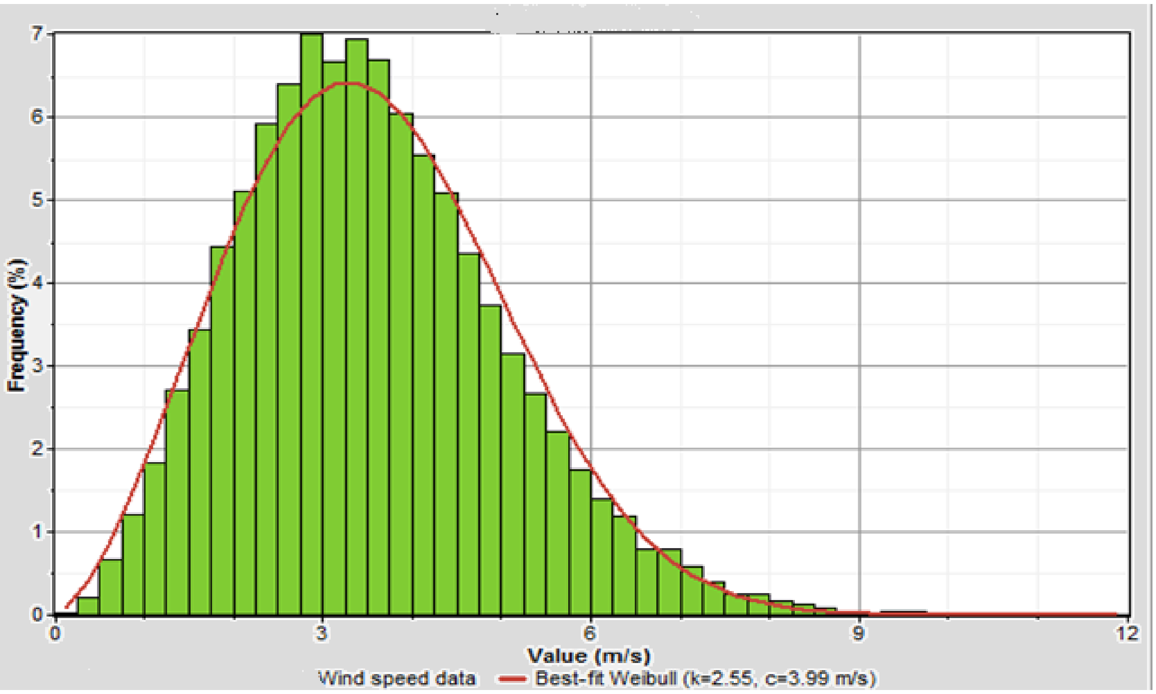
Moyale annual observed and Weibull distribution



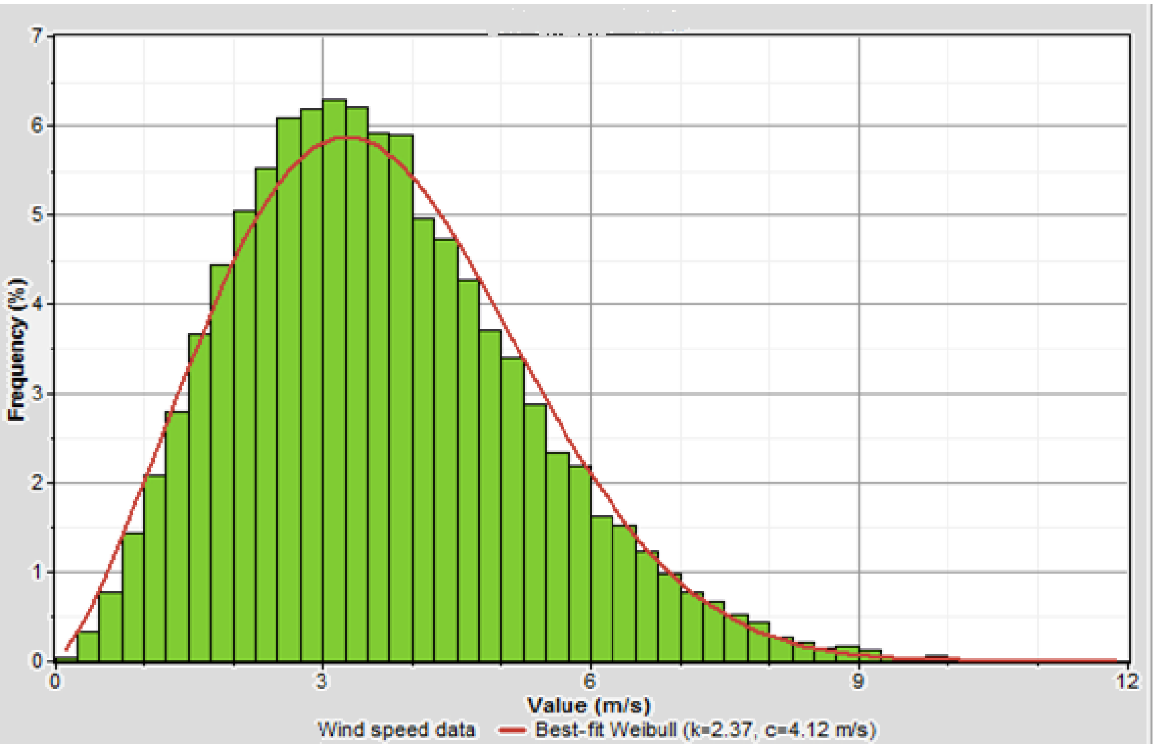
Nazareth annual observed and Weibull distribution



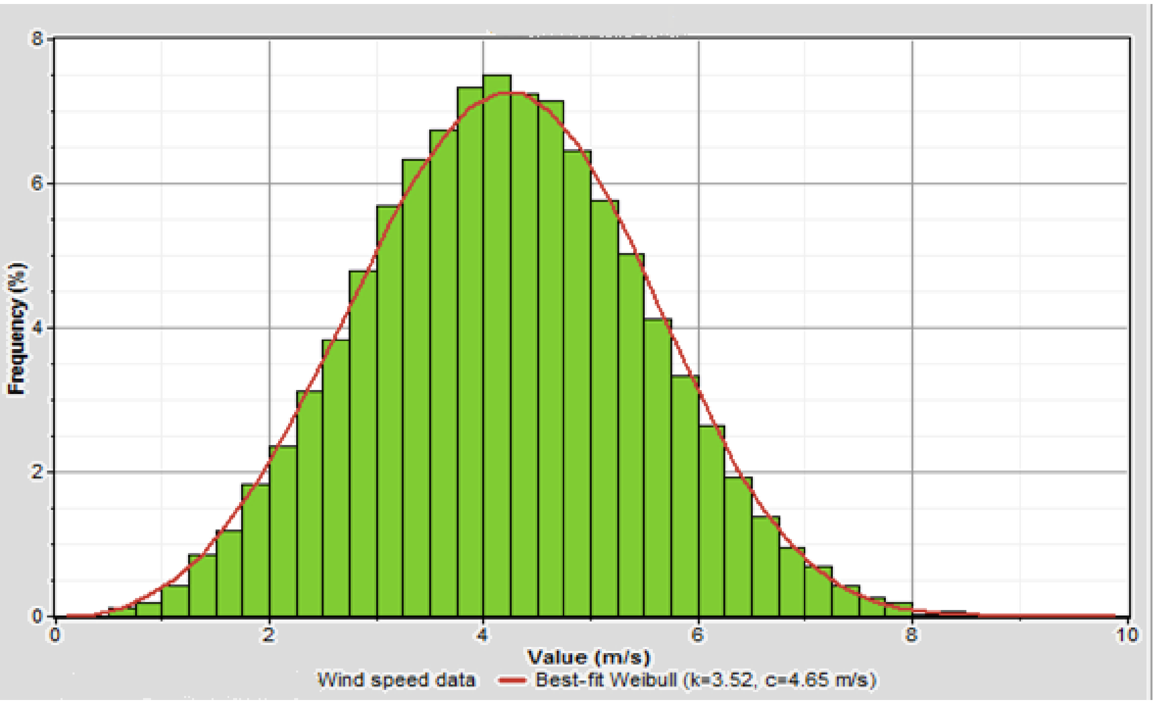
Yabelo annual observed and Weibull distribution



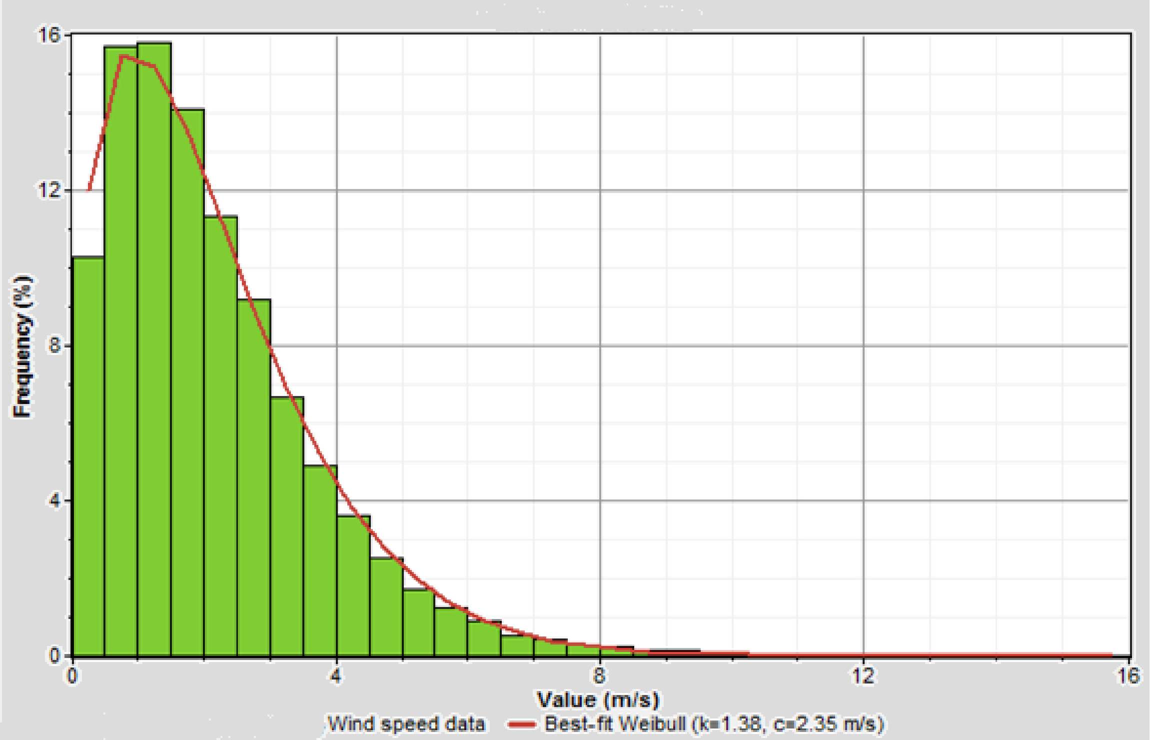
Jijiga annual observed and Weibull distribution



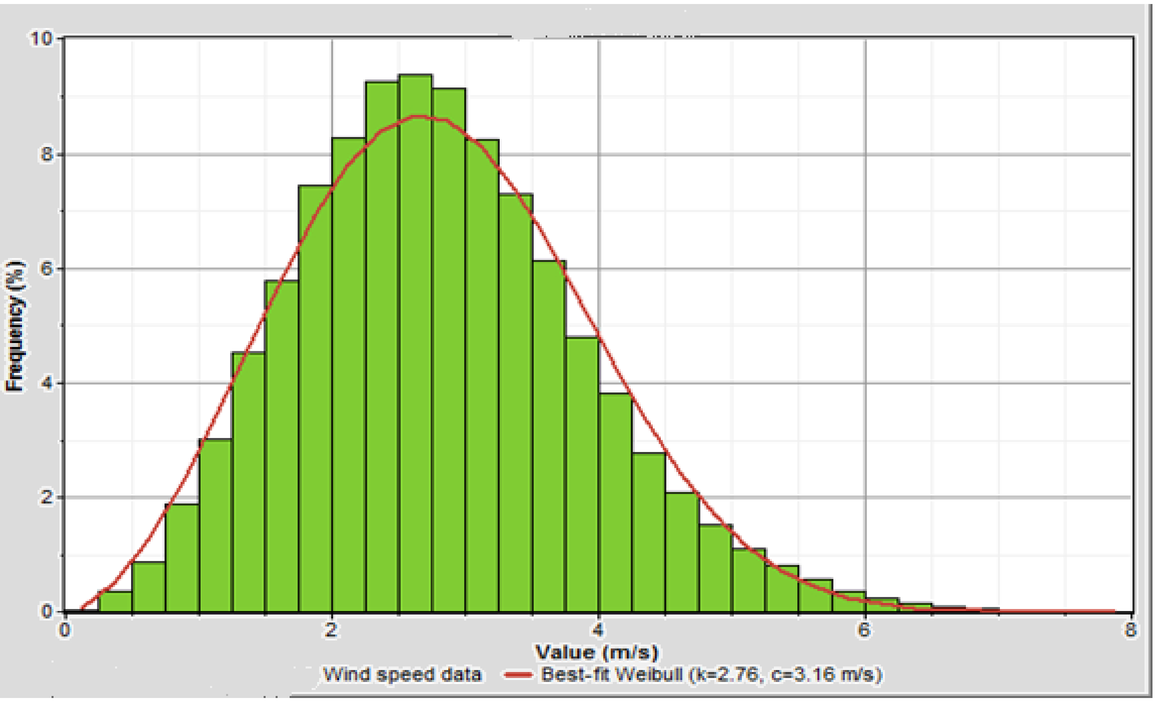
Assosa annual observed and Weibull distribution



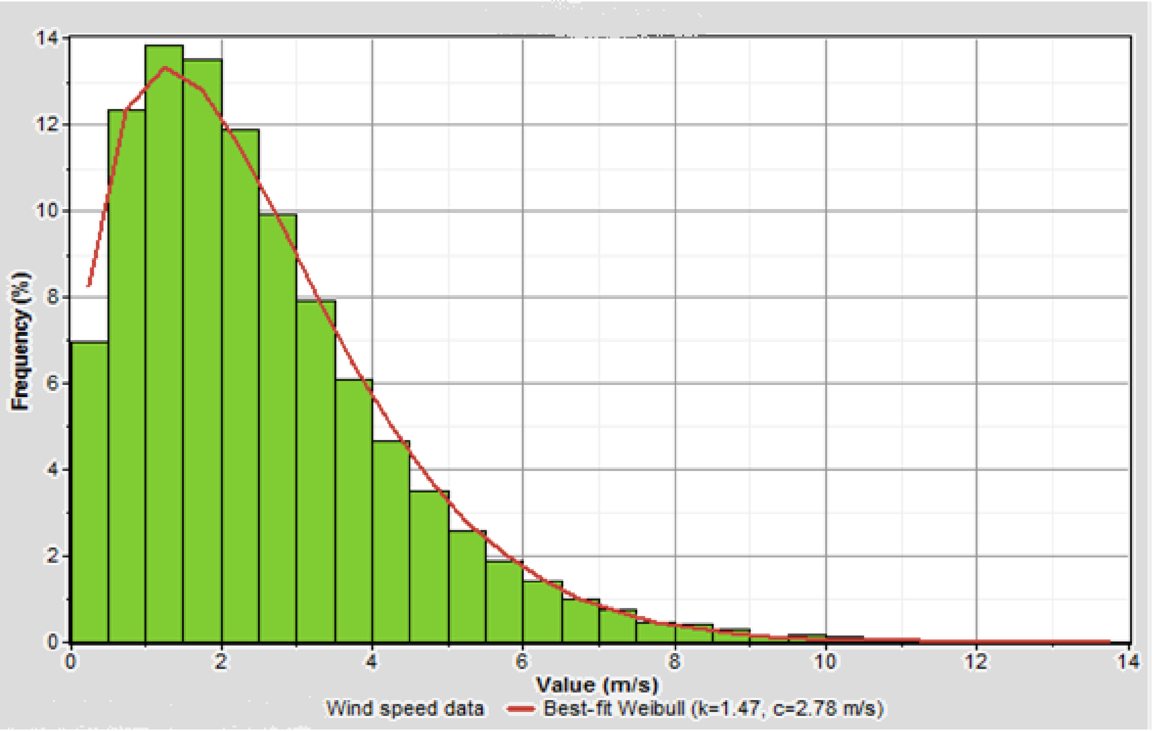
Aykel annual observed and Weibull distribution



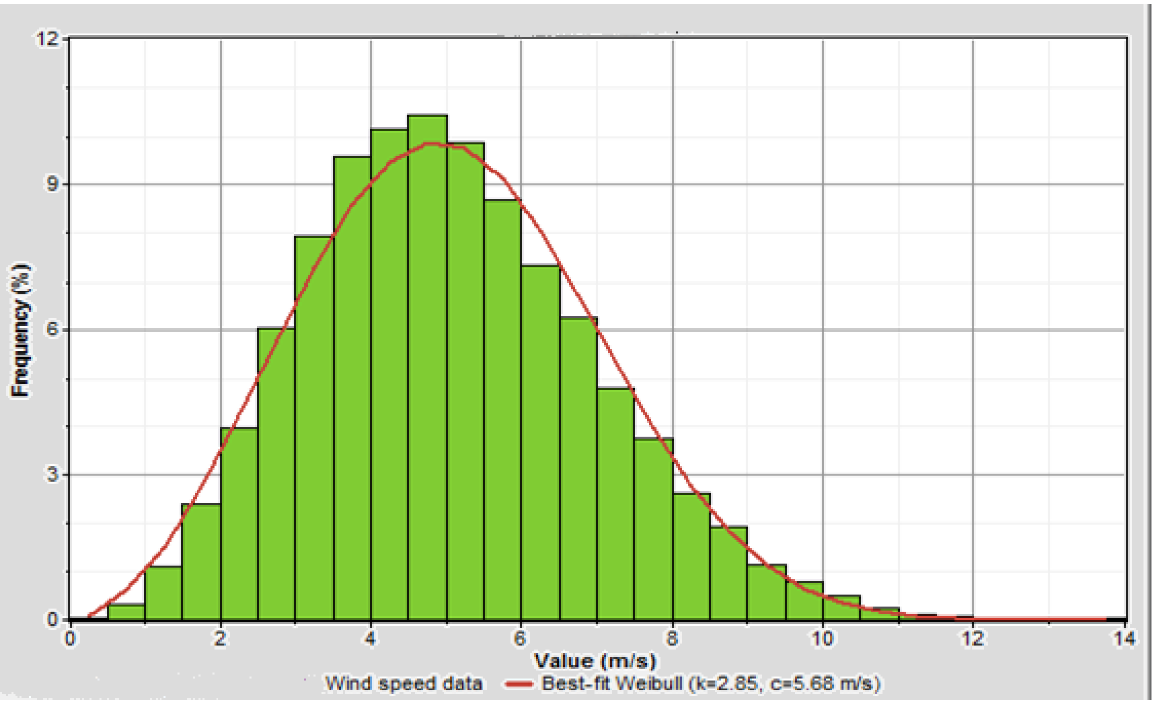
Dupti annual observed and Weibull distribution



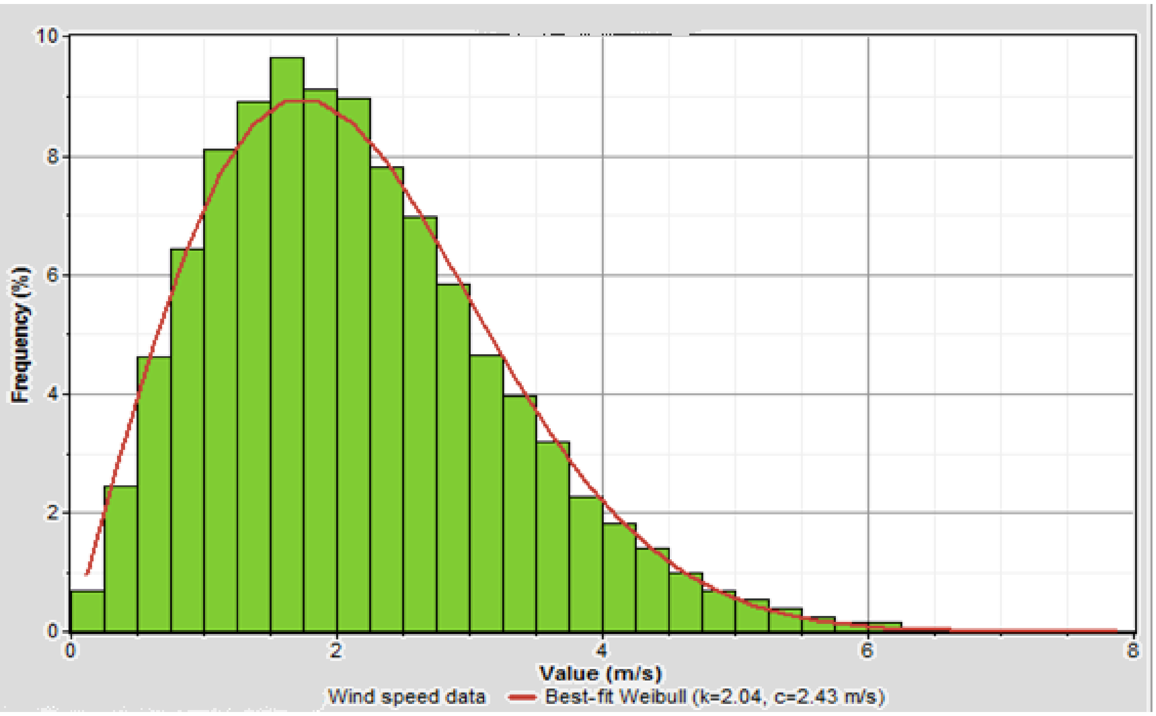
Gewane annual observed and Weibull distribution



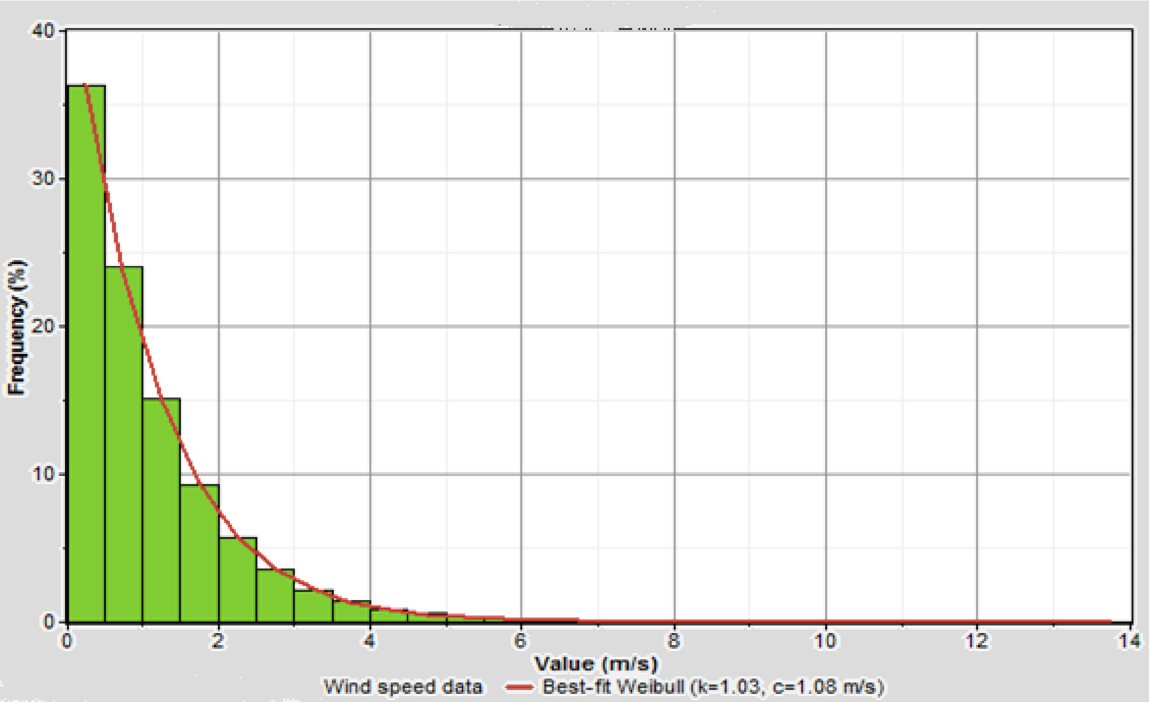
Gelmso annual observed and Weibull distribution



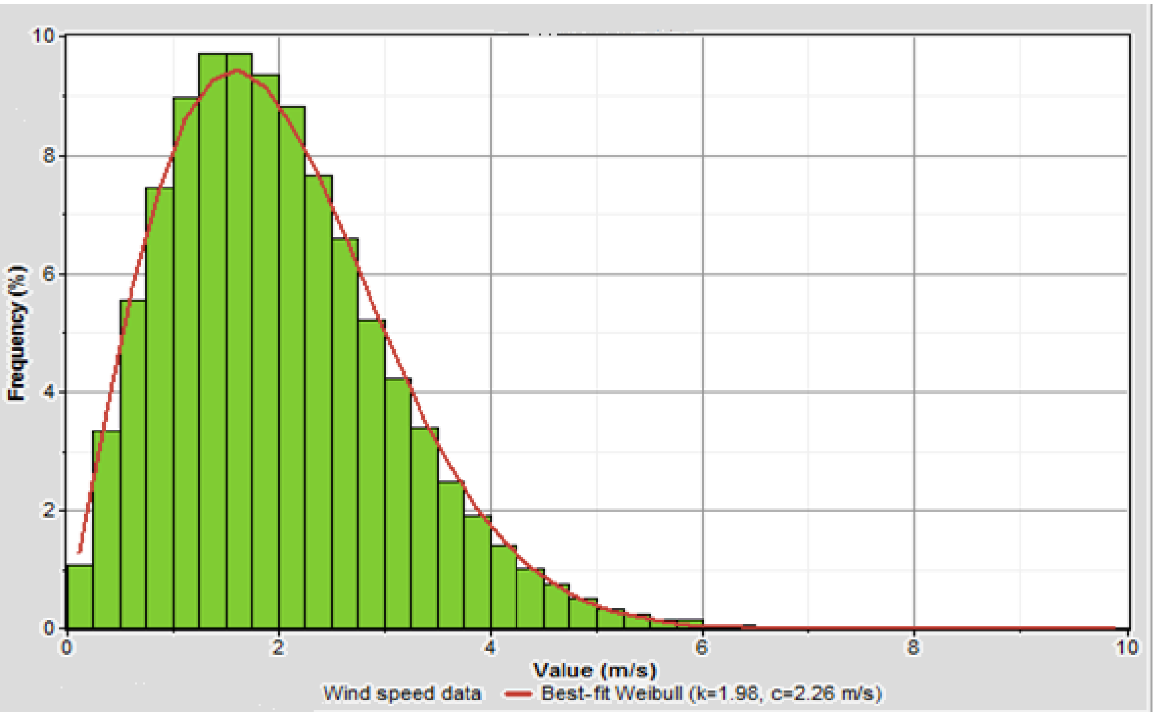
Addis Ababa annual observed and Weibull distribution



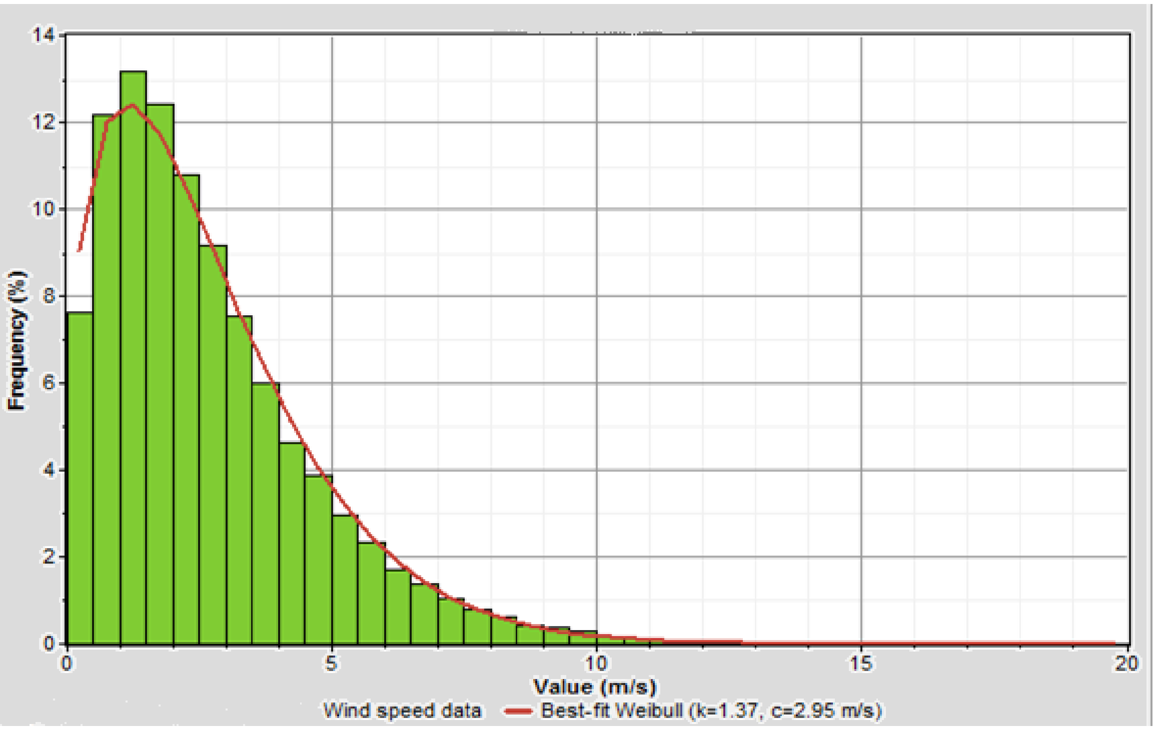
Hagermariam annual observed and Weibull distribution



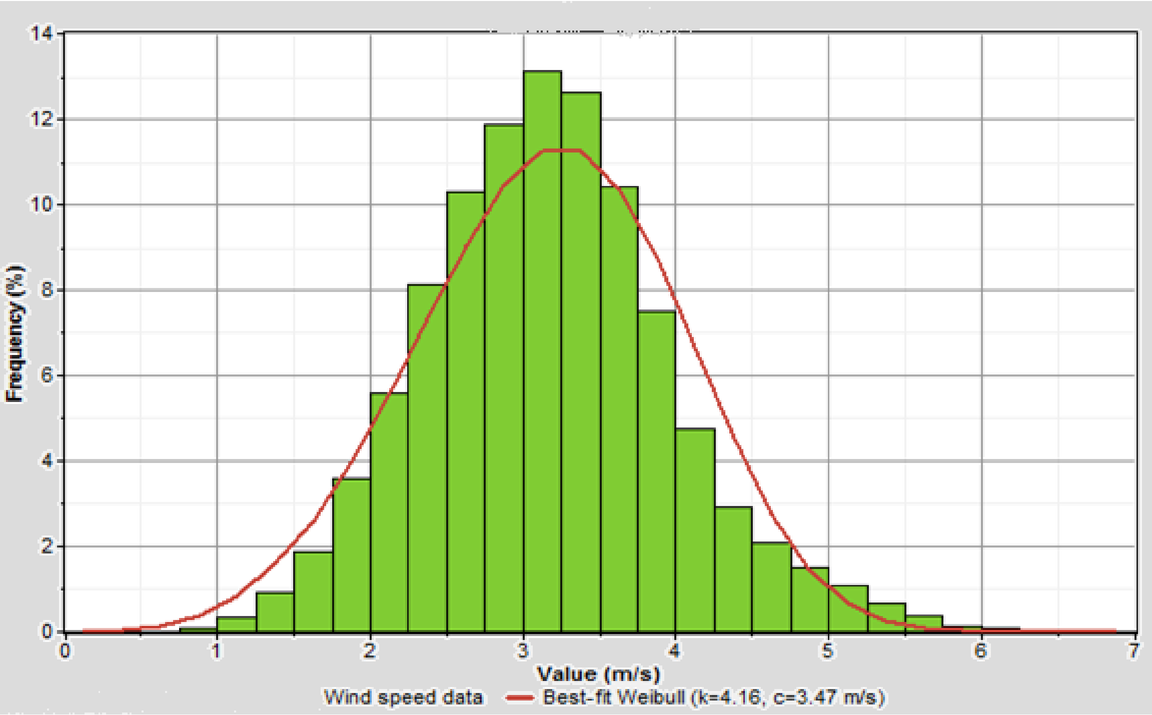
Kibremengist annual observed and Weibull distribution



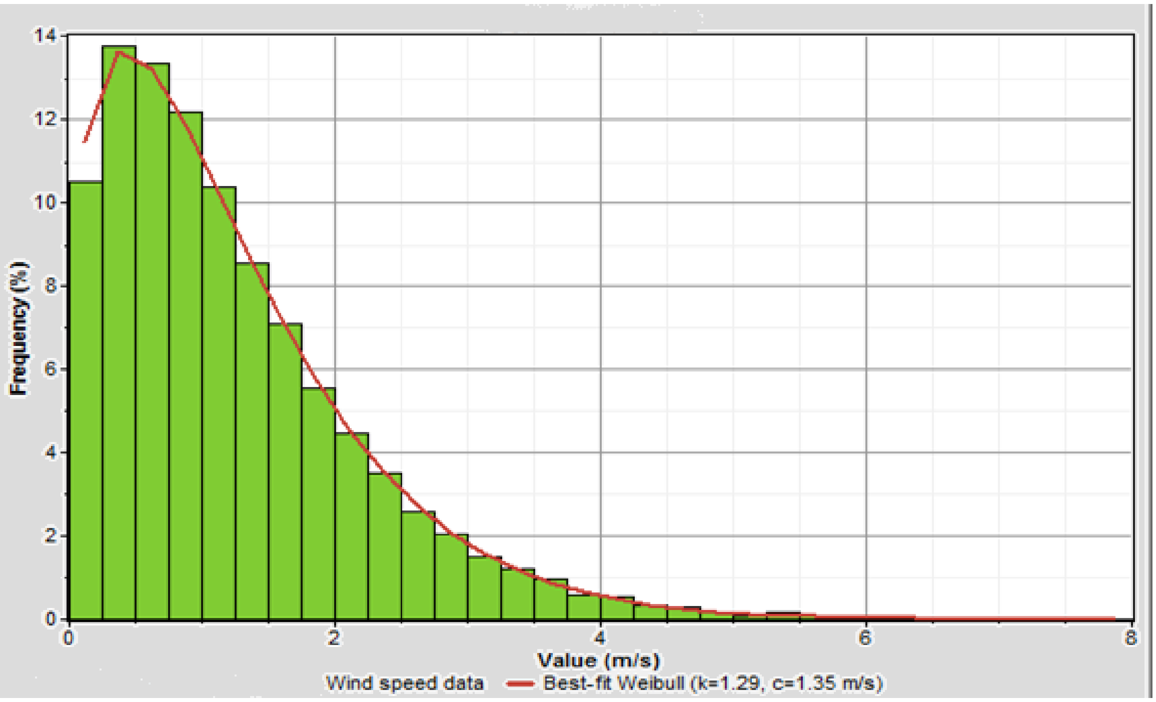
Debremarkos annual observed and Weibull distribution



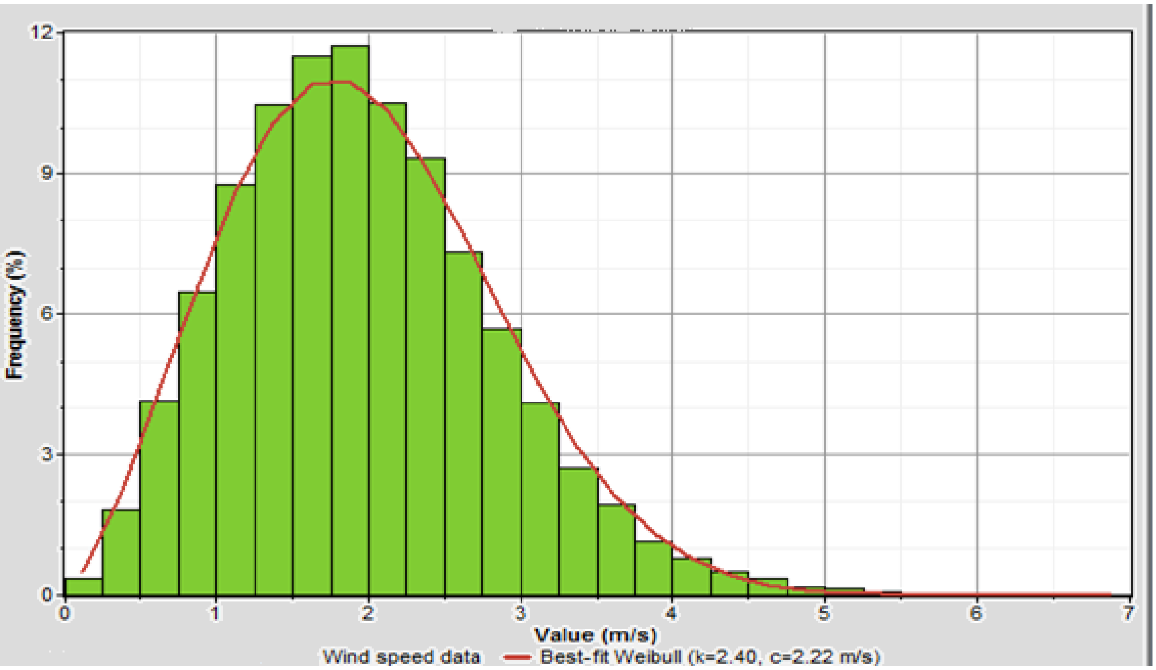
Debrezit annual observed and Weibull distribution



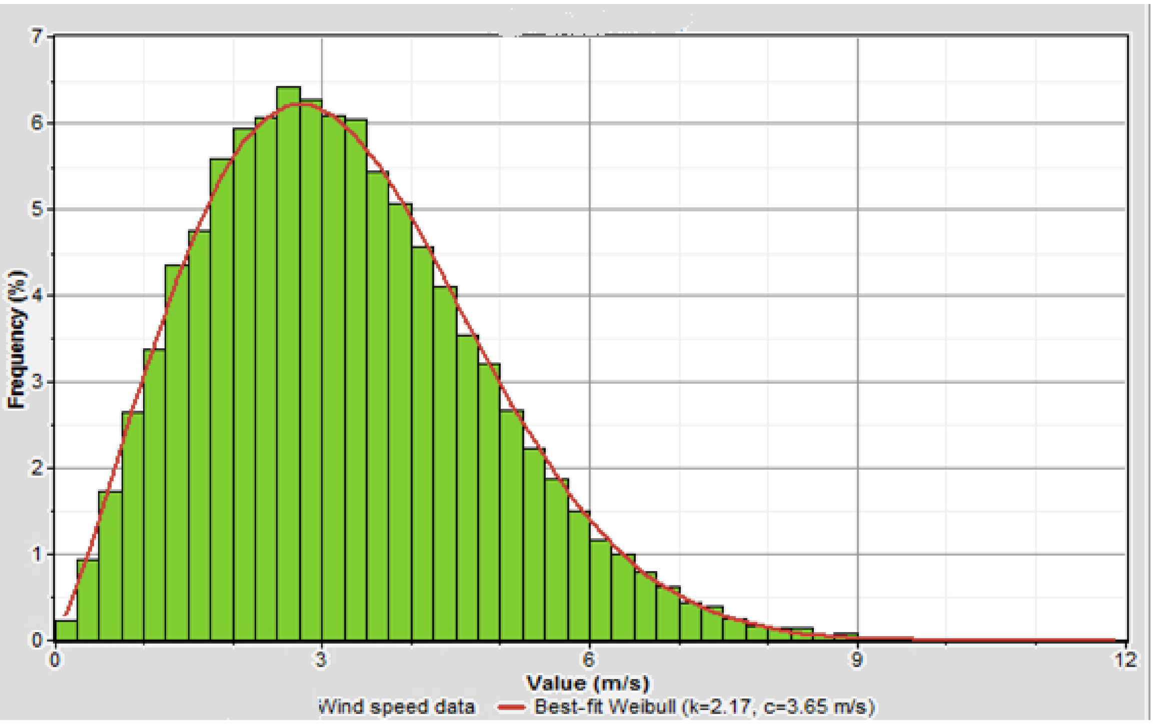
Mega annual observed and Weibull distribution



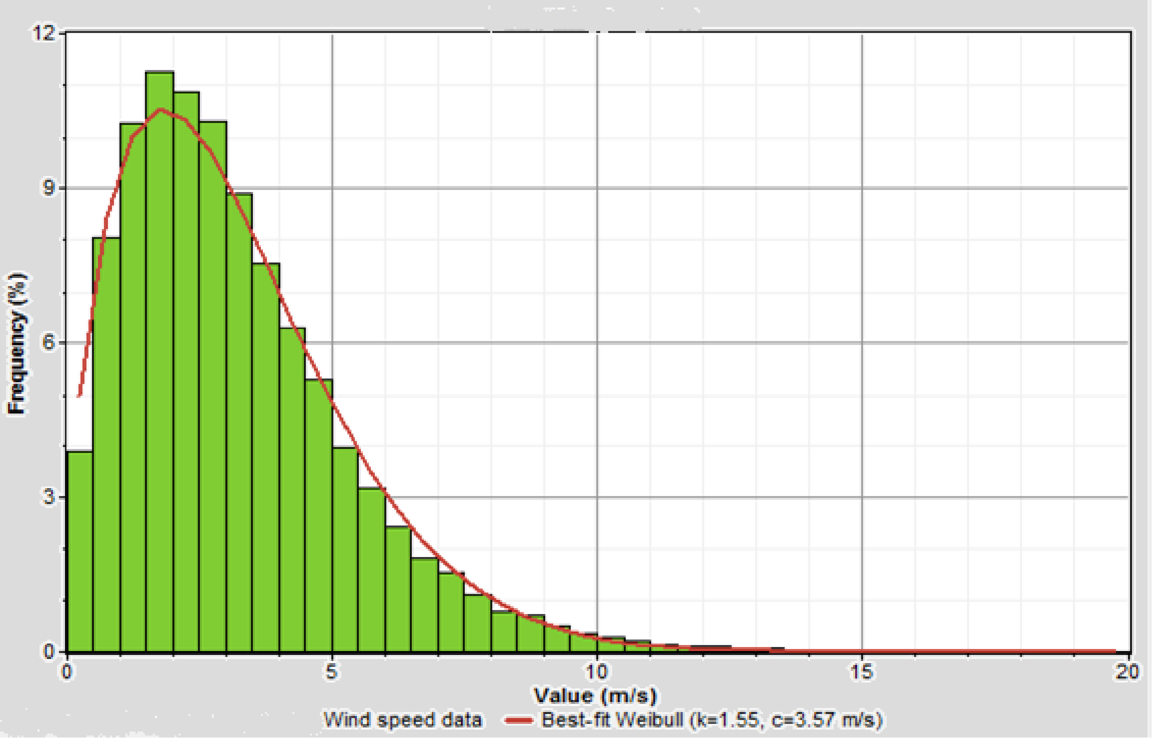
Pawe annual observed and Weibull distribution



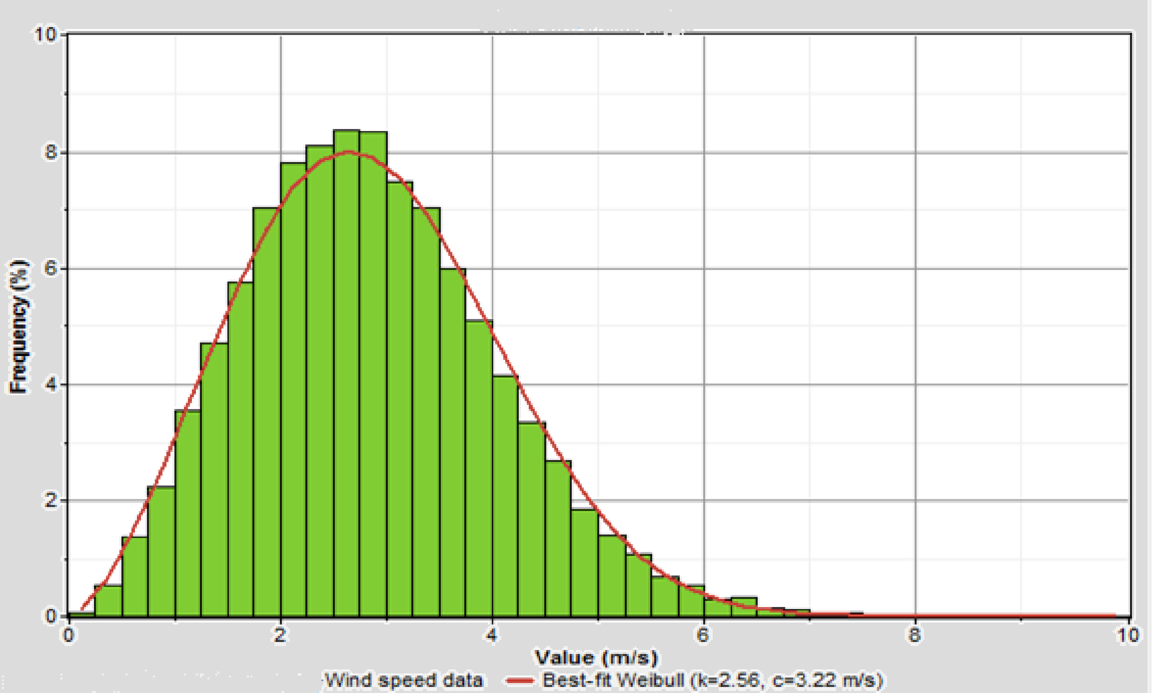
Gimbi annual observed and Weibull distribution



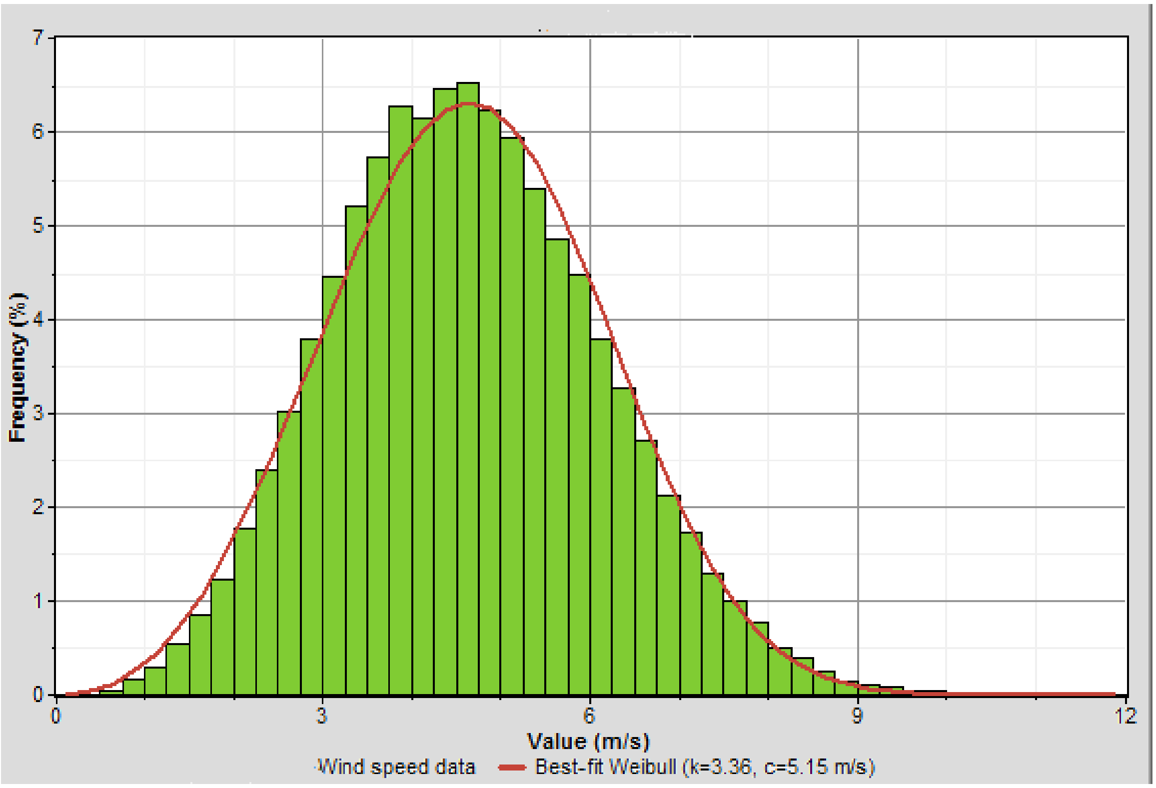
Bilate annual observed and Weibull distribution



Harar annual observed and Weibull distribution

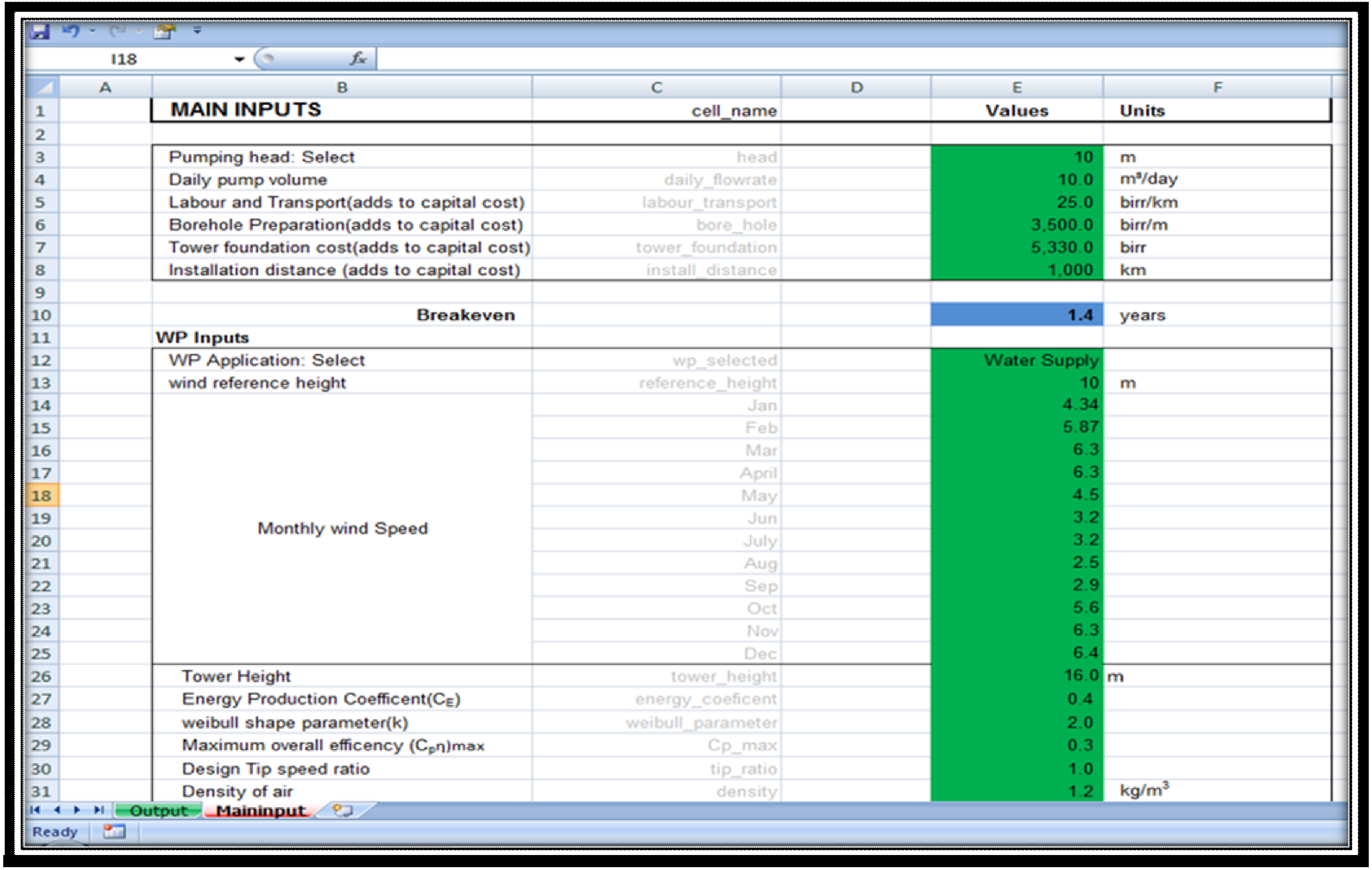


Sholagebya annual observed and Weibull distribution

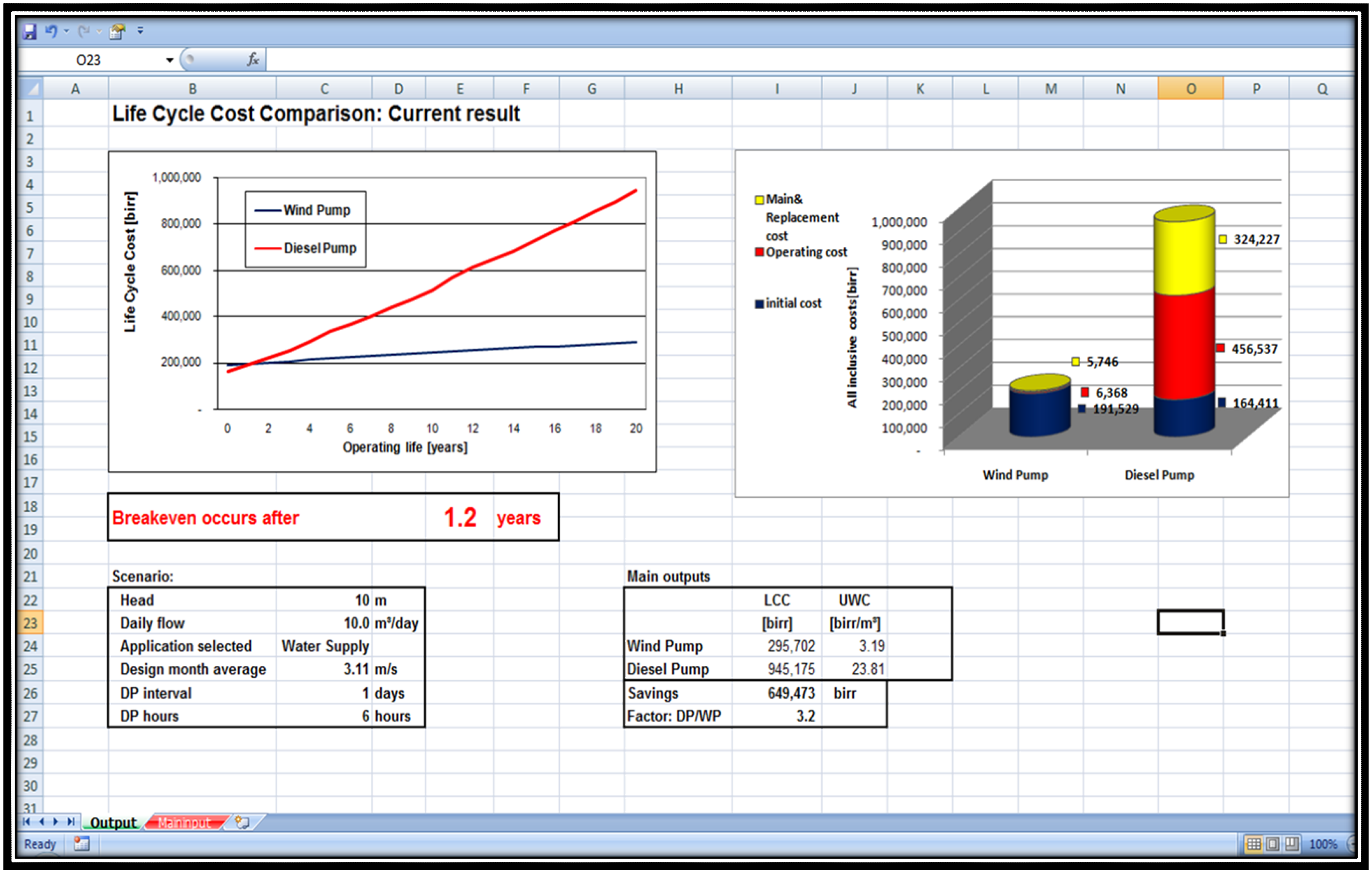


Mehalemeda annual observed and Weibull distribution

Appendix B: Cost Analysis Model Sheet



	A	B	C	D	E	F
1		**MAIN INPUTS**	cell_name		**Values**	**Units**
2						
3		Pumping head: Select	head		10	m
4		Daily pump volume	daily_flowrate		10.0	m^3/day
5		Labour and Transport(adds to capital cost)	labour_transport		25.0	birr/km
6		Borehole Preparation(adds to capital cost)	bore_hole		3,500.0	birr/m
7		Tower foundation cost(adds to capital cost)	tower_foundation		5,330.0	birr
8		Installation distance (adds to capital cost)	install_distance		1,000	km
9						
10		**Breakeven**			**1.4**	years
11		**WP Inputs**				
12		WP Application: Select	wp_selected		Water Supply	
13		wind reference height	reference_height		10	m
14		Monthly wind Speed	Jan		4.34	
15			Feb		5.87	
16			Mar		6.3	
17			April		6.3	
18			May		4.5	
19			Jun		3.2	
20			July		3.2	
21			Aug		2.5	
22			Sep		2.9	
23			Oct		5.6	
24			Nov		6.3	
25			Dec		6.4	
26		Tower Height	tower_height		16.0	m
27		Energy Production Coefficent(C_E)	energy_coeficent		0.4	
28		weibull shape parameter(k)	weibull_parameter		2.0	
29		Maximum overall efficency ($C_p\eta$)max	Cp_max		0.3	
30		Design Tip speed ratio	tip_ratio		1.0	
31		Density of air	density		1.2	kg/m^3



Life Cycle Cost Comparison: Current result

Breakeven occurs after 1.2 years

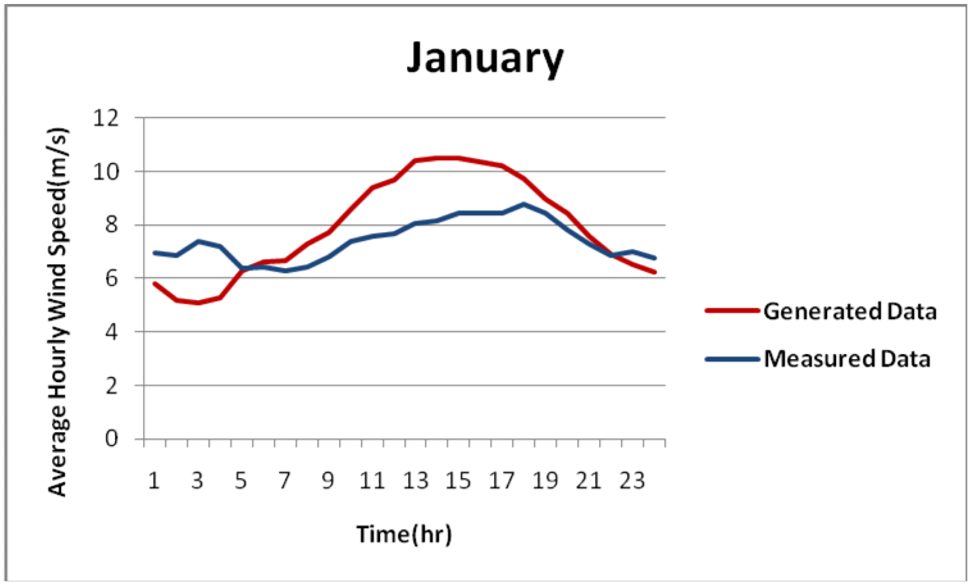
Scenario:

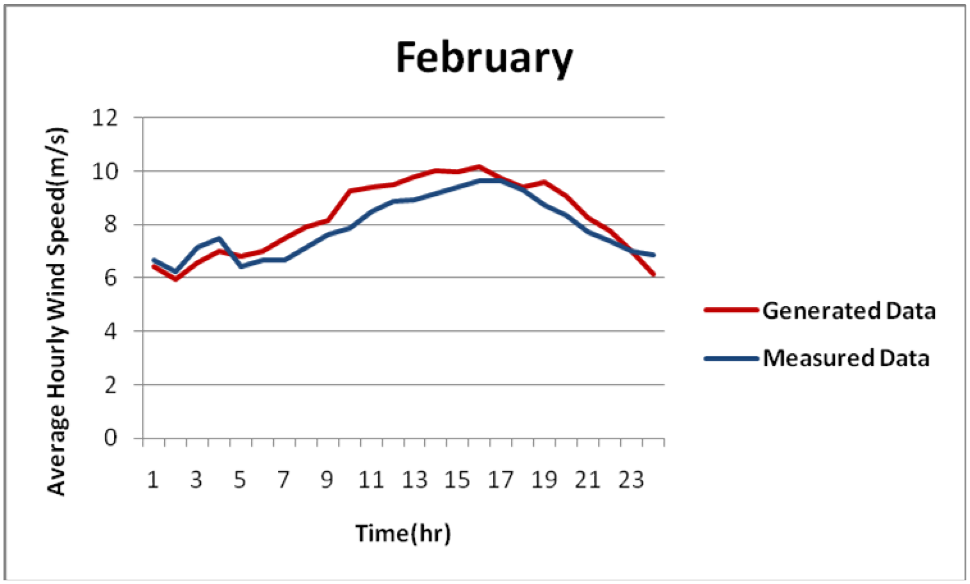
Head	10	m
Daily flow	10.0	m³/day
Application selected	Water Supply	
Design month average	3.11	m/s
DP interval	1	days
DP hours	6	hours

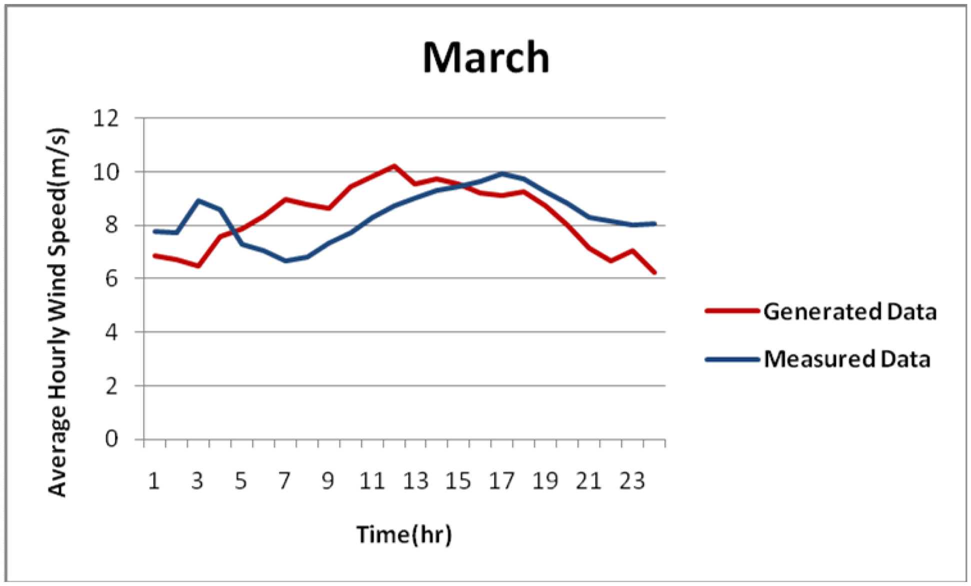
Main outputs

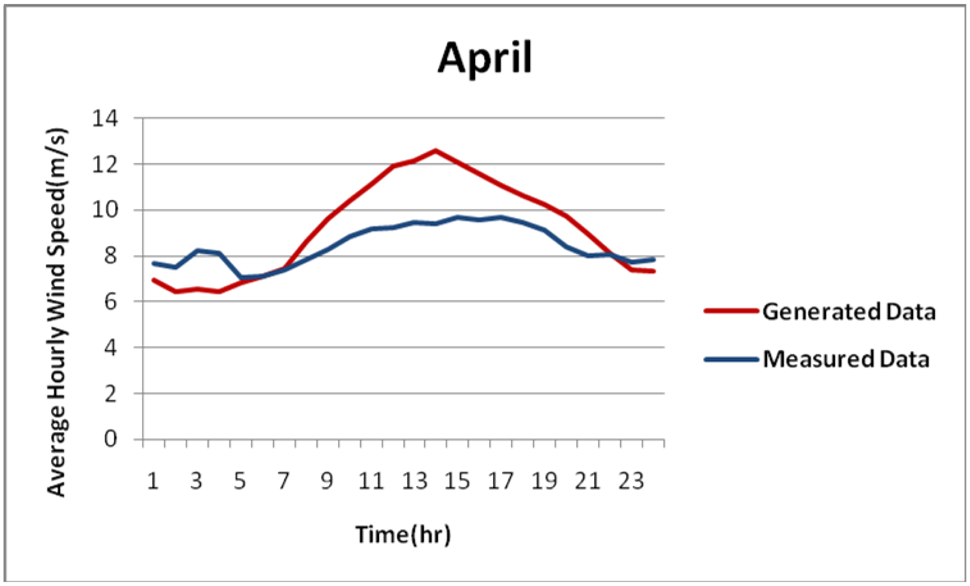
	LCC	UWC
	[birr]	[birr/m³]
Wind Pump	295,702	3.19
Diesel Pump	945,175	23.81
Savings	649,473	birr
Factor: DP/WP	3.2	

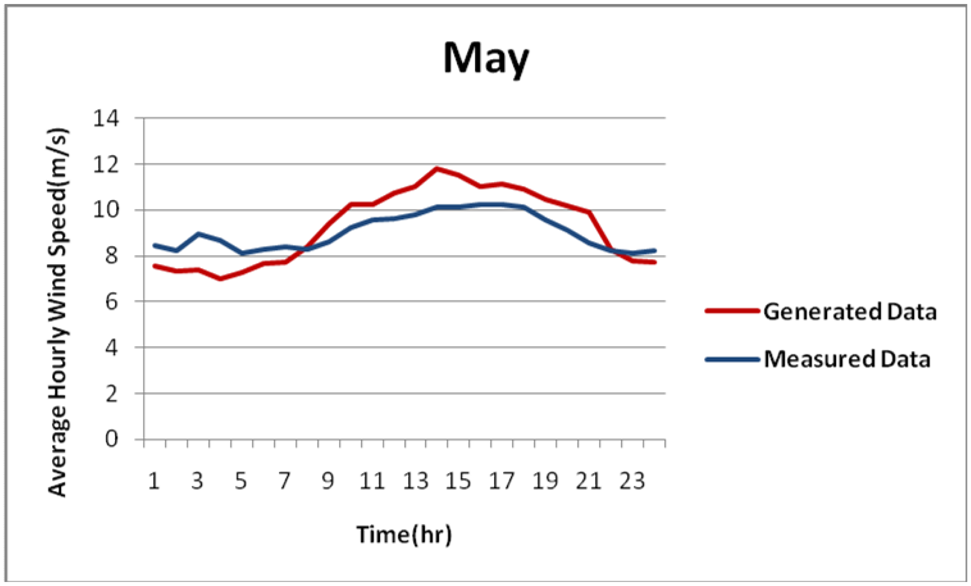
Appendix C: Diurnal Measured and Generated Wind Speed Profile

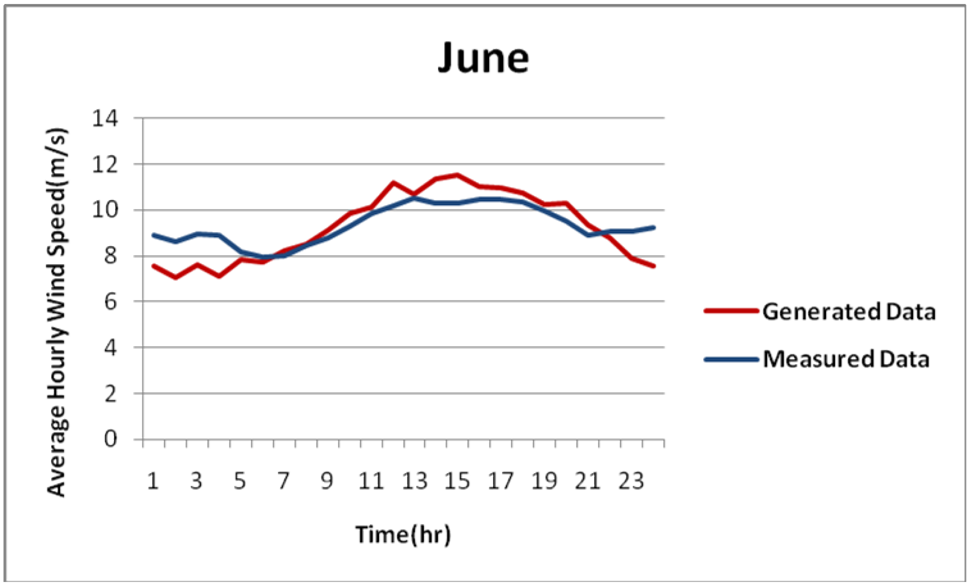


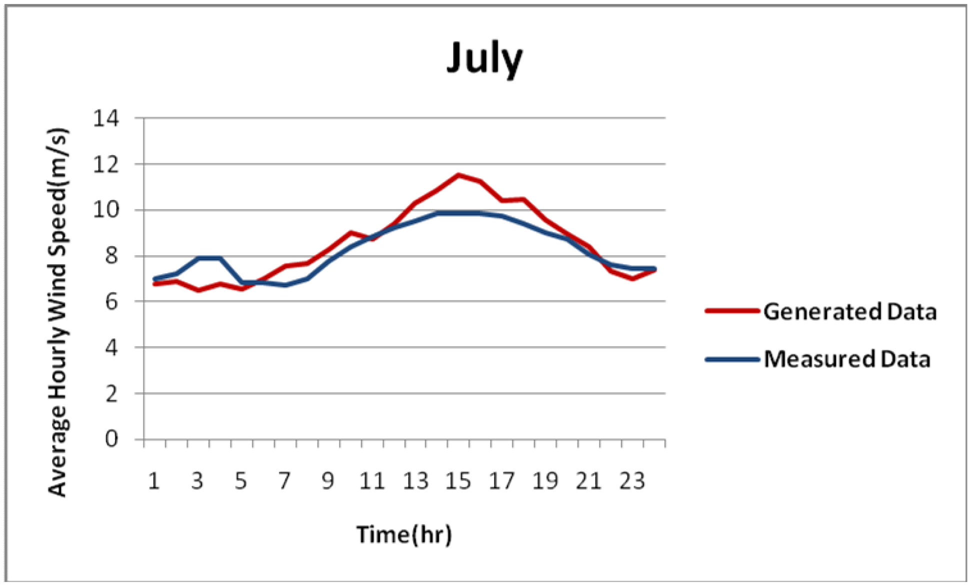


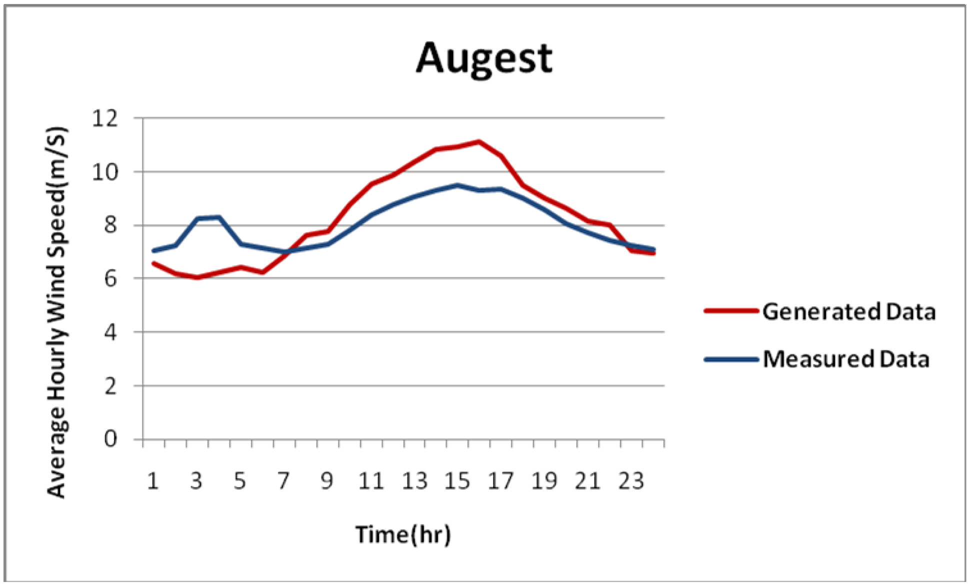

March
Average Hourly Wind Speed(m/s)
12
10
8
6
4
2
0
1
3
5
7
9
11
13
15
17
19
21
23
Time(hr)
Generated Data
Measured Data

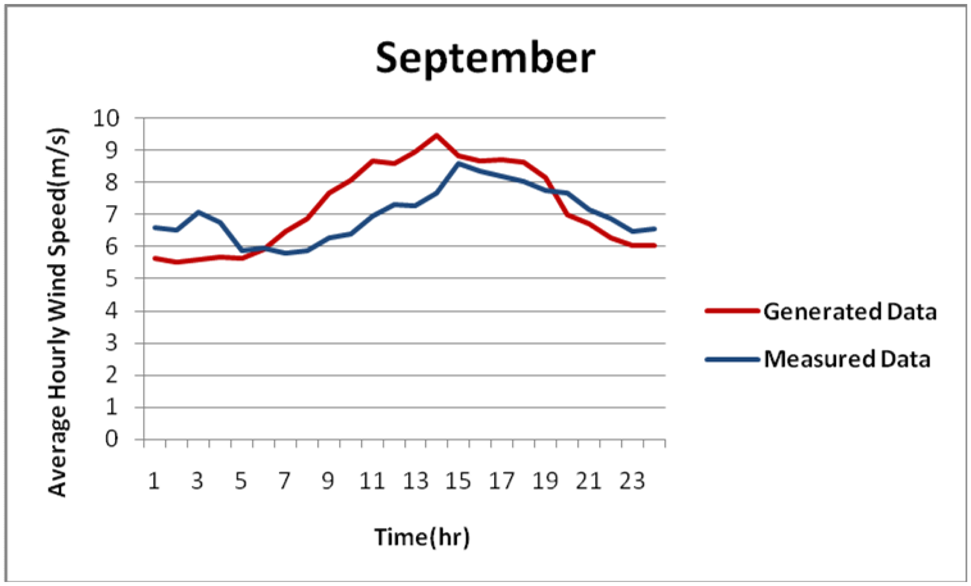

April
Average Hourly Wind Speed(m/s)
14
12
10
8
6
4
2
0
1
3
5
7
9
11
13
15
17
19
21
23
Time(hr)
Generated Data
Measured Data

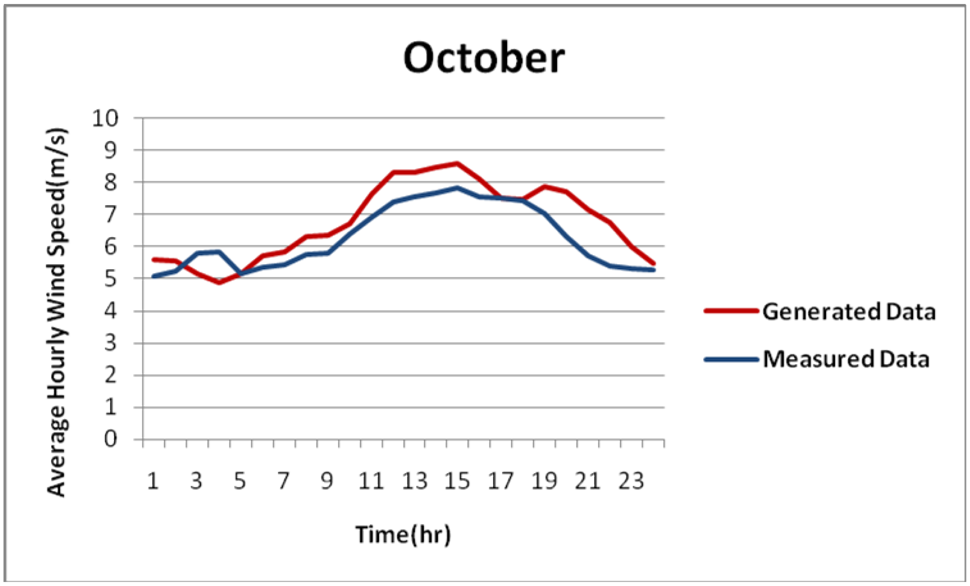

May
Average Hourly Wind Speed(m/s)
14
12
10
8
6
4
2
0
1
3
5
7
9
11
13
15
17
19
21
23
Time(hr)
Generated Data
Measured Data

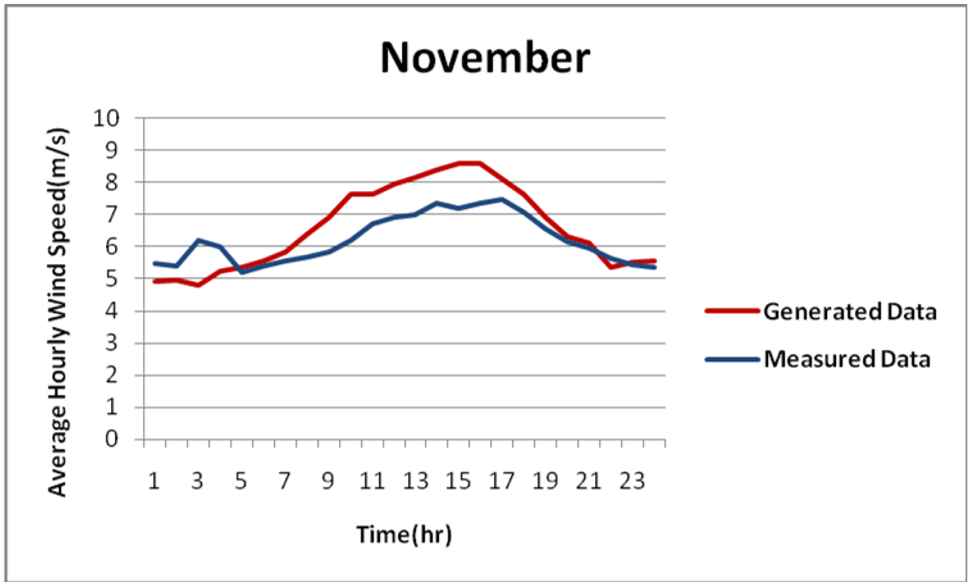

June
Average Hourly Wind Speed(m/s)
14
12
10
8
6
4
2
0
1
3
5
7
9
11
13
15
17
19
21
23
Time(hr)
Generated Data
Measured Data

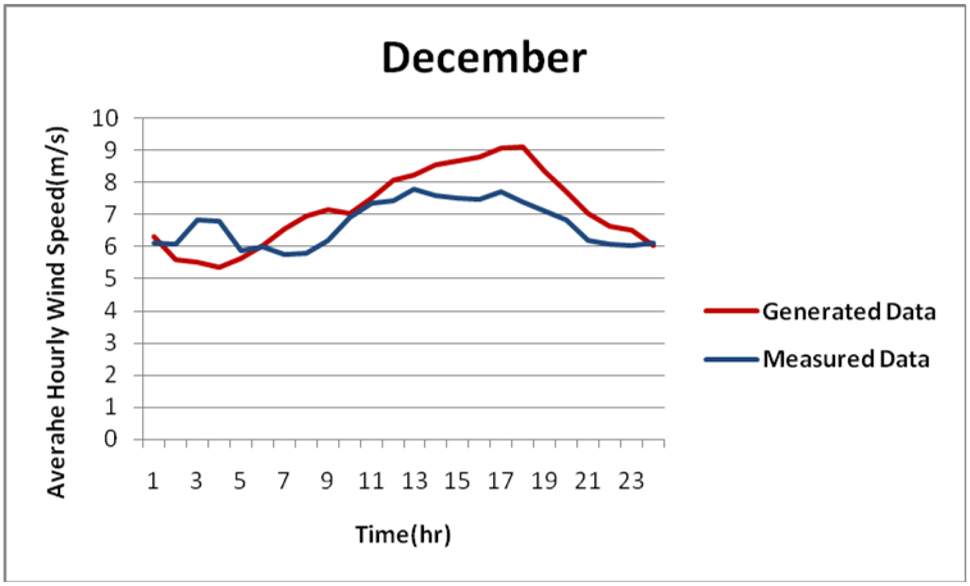

July
Average Hourly Wind Speed(m/s)
14
12
10
8
6
4
2
0
1
3
5
7
9
11
13
15
17
19
21
23
Time(hr)
Generated Data
Measured Data

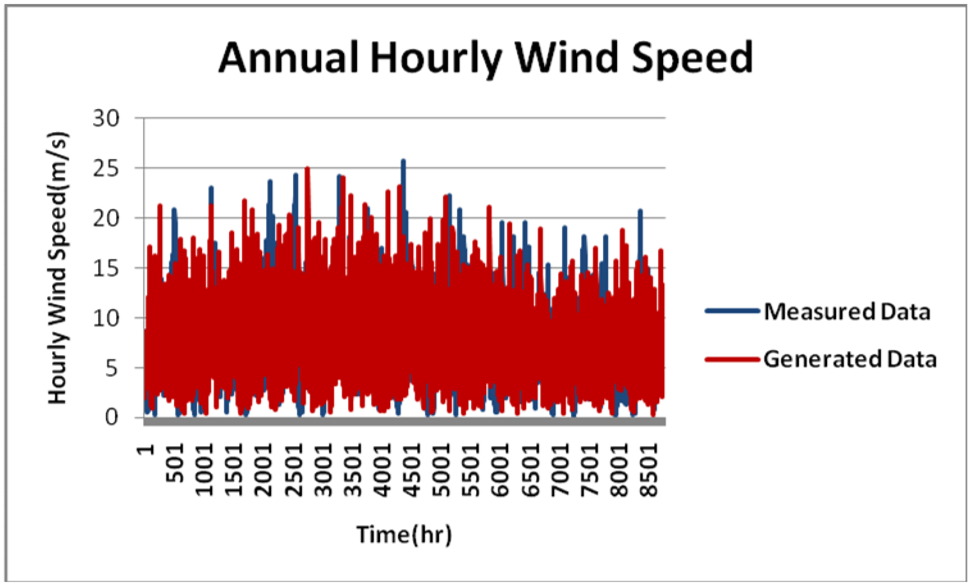

Augest
Average Hourly Wind Speed(m/S)
12
10
8
6
4
2
0
1
3
5
7
9
11
13
15
17
19
21
23
Time(hr)
Generated Data
Measured Data

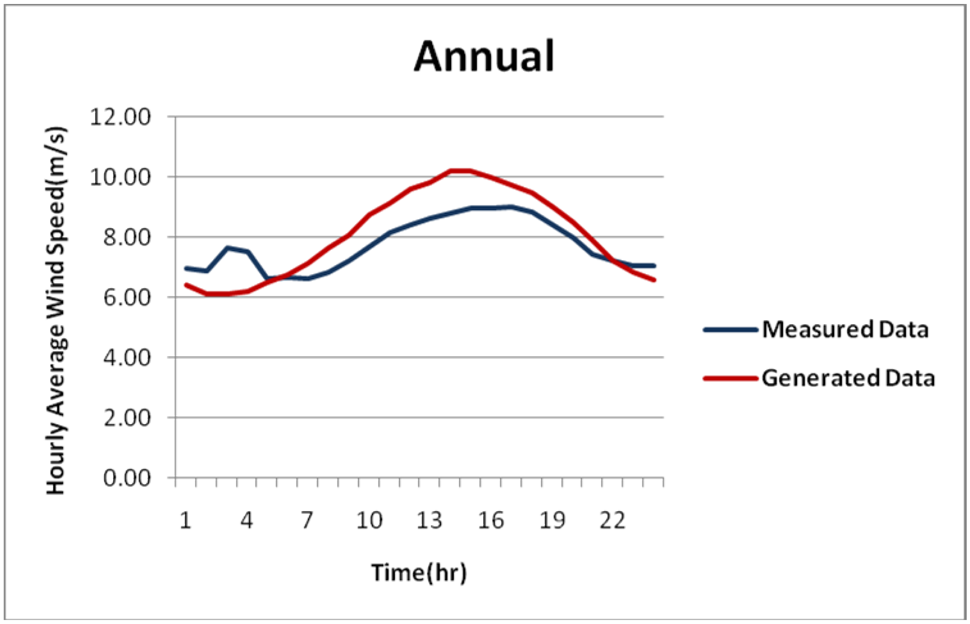

September
Average Hourly Wind Speed(m/s)
10
9
8
7
6
5
4
3
2
1
0
1
3
5
7
9
11
13
15
17
19
21
23
Time(hr)
Generated Data
Measured Data


October
Average Hourly Wind Speed(m/s)
10
9
8
7
6
5
4
3
2
1
0
1
3
5
7
9
11
13
15
17
19
21
23
Time(hr)
Generated Data
Measured Data


November
Average Hourly Wind Speed(m/s)
10
9
8
7
6
5
4
3
2
1
0
1
3
5
7
9
11
13
15
17
19
21
23
Time(hr)
Generated Data
Measured Data


December
Averahe Hourly Wind Speed(m/s)
10
9
8
7
6
5
4
3
2
1
0
1
3
5
7
9
11
13
15
17
19
21
23
Time(hr)
Generated Data
Measured Data


Annual Hourly Wind Speed
Hourly Wind Speed(m/s)
30
25
20
15
10
5
0
1
501
1001
1501
2001
2501
3001
3501
4001
4501
5001
5501
6001
6501
7001
7501
8001
8501
Time(hr)
Measured Data
Generated Data


Annual
Hourly Average Wind Speed(m/s)
12.00
10.00
8.00
6.00
4.00
2.00
0.00
1
4
7
10
13
16
19
22
Time(hr)
Measured Data
Generated Data

REFERENCES

[1] Joop Van and Paul smulders, *Wind Pumping Hand Book*: *World Bank Technical paper (ISSN 0253-7494:No. 101)*, Washington D.C USA, 1989

[2] Sathyajith Mathew. *Wind Energy Fundamentals, Resource Analysis and Economics. Springer-Verlag Berlin Heiderberg,2006*

[3] Lysen.E.H *Introduction to Wind Energy.* 2th Edition, Netherlands: Eindhoven university of Technology, May 1983.

[4] Rastogi.T *Wind Pump Hand Book*, Tata Energy Research Institute, Paris, November, 1982.

[5] Getachew Bekele, Bjorn Palm (2008).*Wind Energy Potential Assessment at Four Typical Locations in Ethiopia*. Journal of Applied Energy 86(2009) 388-396.

[6] Ramachandra.T.V, Subramantan.D.K and Joshi.N.V (1997).*Wind Energy Potential Assessment in Uttara Kannade District of Karnataka, India*. Journal of Renewable Energy (4) 585-611.

[7] Teferi Taye (1999). *Wind Energy Harnessing-Theory and The Ethiopian Experience* .Journal of ESME II (2).

[8] Gary Hishbergy. *Water Pumping Windmill Book*, Andover.Masasachusetts: Brick house publishing Co.Inc. 1982.

[9] W.Wolde Ghiorgious. *Wind Energy Survey in Ethiopia.* Journal of Solar and Wind Technology 5(4) 341-351.

[10] Michel Louge. *A Simple Wind Pump Analysis.* www.mae.cornell.edu

[11] Smulders. P.T.,Rijs.R.P.P. *An Analysis of Wind Rope Pump System.* Netherlands: Eindhoven university of Technology, June 2006.

[12] Drake F. and Yacob Mulugetta (1996). *Assessment of solar and wind energy resources in Ethiopia, University of Leeds. UK*

Declaration

I, the undersigned declare that this thesis is my original work and has not been presented for a degree in any other university and that all sources of material used for this thesis have been dully acknowledged.

Dejene Assefa ______________

November, 2010 Signature