Wind Resource Assessment and Wind Farm Modeling in Mossobo-Harena Area, North Ethiopia

Addisu Dagne Zegeye

Abstract— Although Ethiopia doesn't have significant fossil fuel resource it is endowed with huge amount of renewable energy resources such as hydro, wind, geothermal and solar power. However, only a small portion of these resources has been utilized so far and less than 30 percent of the nation's population has access to electricity. The wind energy potential of the country is estimated to be up to 10GW. Yet less than 5% of this potential is developed so far. One of the reasons for this low utilization of wind energy in Ethiopia is absence of a reliable and accurate wind atlas and resource maps. Development of reliable and accurate wind atlas and resource maps helps to identify candidate sites for wind energy applications and facilitates the planning and implementation of wind energy projects. The main purpose of this research is to assess the wind energy potential and model wind farm in Mossobo-Harena site of North Ethiopia. In this research wind data collected over a period of two years from Mossobo-Harena site meteorological station was analyzed using different statistical tools to evaluate the wind energy potential of the area. Average wind speed and power density, distribution of the wind, prevailing direction, turbulence intensity and wind shear profile of the site were determined. Wind Atlas Analysis and Application Programme (WAsP) was used to generate the generalized wind climate of the area and to develop resource maps. Wind Farm layout and preliminary turbine micro-sitting was done taking various factors into consideration. The IEC wind turbine class of the site was determined and appropriate Wind turbine for the study area wind climate was selected and net annual energy production and capacity factor of the wind farm was determined. The measured data analysis conducted indicates that the mean wind speed at 10 and 40 meters above the ground level is 5.12 m/s and 6.41 m/s respectively at measuring site. The measuring site's mean power density was determined to be 138.55 W/m^2 and 276.52 W/m^2 at 10 and 40 meters above the ground level respectively. The prevailing wind direction in the site is from East to South East where about 60 percent of the wind was recorded. The resource grid maps developed by WAsP on 10 km x 10 km area at 50 meter above the ground level indicates that the selected study area has a mean wind speed of 5.58 m/s and mean power density of 146 W/m^2. The average turbulence intensity of the site was found to be 0.136 at 40 meter which indicates that the site has moderate level turbulence level. According to the resource assessment done, the area is classified as wind Class IIIB site. A 2 MW rated power ENERCON E-82 E2 wind turbine which is a IEC Class IIB turbine with 82-meter rotor diameter and 98-meter hub height was selected for estimation of annual energy production on the proposed wind farm. 88 ENERCON E-82 E2 wind turbines were properly sited in the wind farm with recommended spacing between the turbines so as so reduce the wake loss. The rated power of the wind farm is 180.4 MW and the net annual energy production and capacity factor of the proposed wind farm was determined to be 434.315 GWh and 27.48 % after considering various losses in the wind farm.

Index Terms—. WAsP, Wind Speed, Prevailing Wind Direction, Wind Power Density, Annual Energy Production, Wind Atlas, Wind Resource Maps, Wind farm, capacity factor

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1 INTRODUCTION

Ethiopia is endowed with huge amount of renewable energy resources such as hydro, wind, geothermal and solar power. The hydroelectric, wind and geothermal energy resources are estimated to be 45,000 MW, 10,000 MW, and 5,000 MW respectively. These resources can be harvested to generate approximately 60,000 MW of electricity [4].

Ethiopia's current total electrical energy installed capacity is about 4,250 MW. The country's main electrical energy supply is hydropower with around 90% of the total installed capacity coming from hydropower power plants. The wind farms contribute to 8 % of the installed capacity and the rest 2 % is from diesel generators and geothermal power plants. The country's installed capacity is expected to reach 10,000 MW when the country's major ongoing hydropower, wind power and geothermal projects are completed in the coming years [4]. The reliance on hydropower for power electrical energy production is a risky and too unreliable. In times of drought and during periods of high demand it cannot supply enough electricity. To solve this problem Ethiopia needs to look for alternative

energy resources which can support Hydropower during dry periods where the water level in the dams is low. Wind Energy is believed be a good alternative source of electrical energy production due to its complementary nature of with hydropower. During the rainy season the country sees low wind and in the dry season the potential of wind becomes high. This creates favorable conditions to use both. Combining the two, wind and hydropower, will add value to the hydropower plants by elongating their operational time (water saving through wind).

Ethiopian Electric Power (EEP) has been undergoing feasibility study in different areas of the country to identify potential sites in Ethiopia. Almost 80% of the identified favorable sites for wind power development are within the Somali Region of Ethiopia, most of which would require long transmission lines to the Ethiopian cities. The northern and central Rift Valley areas of the country have also a good wind speed potential suitable for development of wind farms.

The EEP has been involved in construction of wind farms in different area of the country. Construction of Ashegoda wind farm (120 MW), Adama I wind farm (51 MW) and Adama II wind farm (153 MW) is completed and all the three wind farms are operational and deliver power to the national grid. Construction of Ayisha I wind farm (120 MW), Ayisha II wind farm (120 MW) is going in Somalia Region of the country. Construction of Ayisha III wind farm (60 MW), Assela Wind farm (100MW), Debre Birhan Wind Farm (100MW), and Galema I Wind farm (250 MW) is also expected to follow [4]. The expansion of Aluto Langano Geothermal Project is also expected to bring its capacity to 70 MW. The wind power and Geothermal projects are part of EEP's aim to increase Ethiopia's electric power generation capacity to 10,000 MW from the current 4,244.67 MW capability [4].
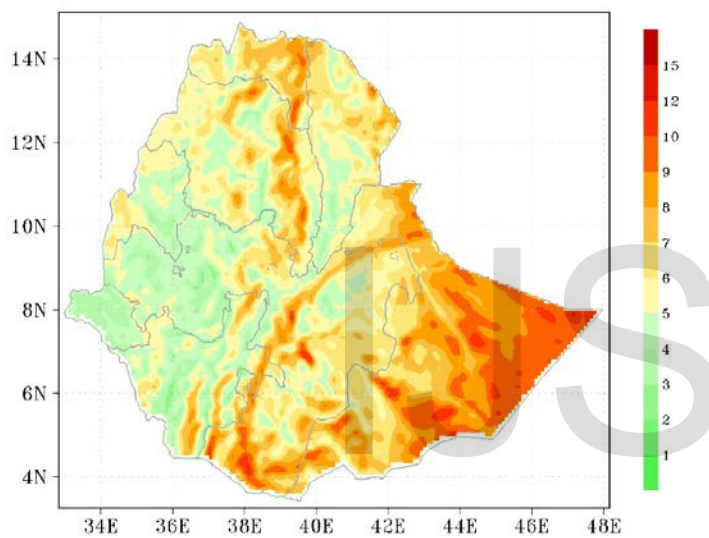

Fig. 1. Distribution of average wind speed in Ethiopia at 50 m above ground level [10]

Due to the absence of a reliable and accurate wind atlas and resource maps, further studies on the assessment of wind energy in Ethiopia are necessary. The detailed wind resource maps and other information contained in wind atlas facilitate the identification of prospective areas for use of wind energy technologies for utility-scale power generation, village power, and off-grid wind energy applications.

The main objective of the study reported in this paper was to conduct wind energy resource assessment, develop wind atlas and resource maps, and model wind farm in Mossobo-Harena area, Tigray Region, North Ethiopia.

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2 METHODOLOGY

2.1 Description of the Study Area

Mossobo-Harena site is located 10 km North of Mekelle City, capital of Tigray Regional State. The measuring mast is located at 13°34'3.54"N latitude, 39°30'44.75"E Longitude and has an altitude of 2400 meter above sea level. The selected study area covers 10 km by 10 km area from the measuring mast bounded by geographical coordinates of 550445.5 m E to 560445.5 m E longitude and 1494964 m N to 1504963.5 m N latitude. The area can be defined as semi-complex terrain. It has different topographical features ranging from 1937 to 2530 meter above sea level, which includes flat terrain around the metrological station, hills, and gorges. The area is covered mostly by bushes and farm land with small trees and few houses.
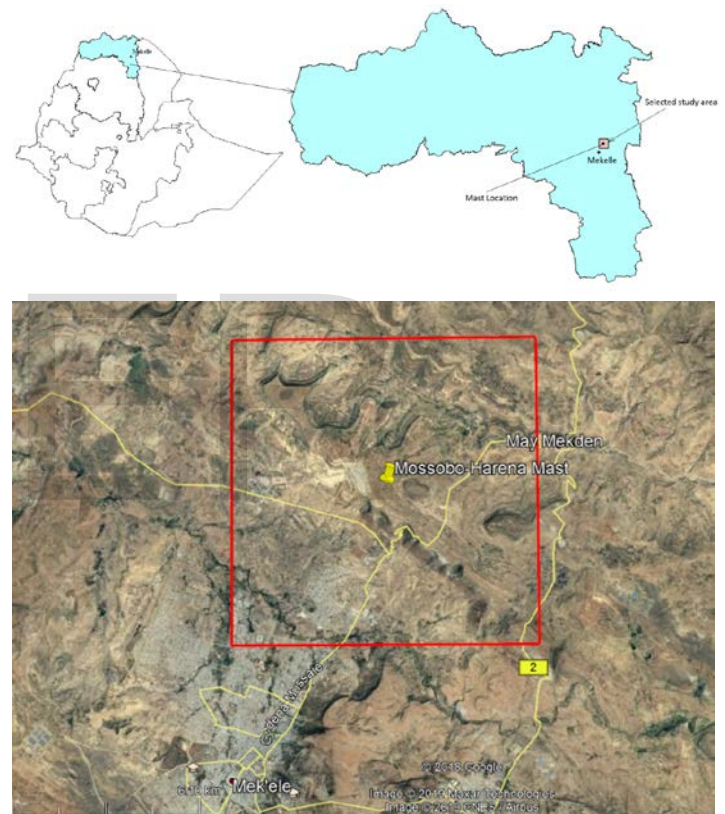

Fig. 2. Map of study area

2.2 Data Collection, Screening and Validation

Wind speed and direction data recorded at a time interval of 10 minutes in Mossobo-Harena metrological station was used for this study. All the collected data was inspected for completeness and any erroneous records. The time series of the data was checked to look for missing data values and a number of data validation routines were used to screen all the data for suspect and erroneous values. General system and parameter checks were used for data screening and validation. The validation checks include: continuity test to identify missing

records in the data, inspection of the average wind speed at each 10-minutes interval records, inspection of negative and unrealistic high wind speed and wind direction records and observation of vertical profile of wind speed on same mast (negative and undefined wind shear coefficients).

Table 1. Data collection

Mast Location	13.5676° N, 39.5124° E
Altitude above sea level [m]	2401
Height of measuring sensors	10, 40 m
Interval of data records	10 minute
Duration of Data Records	01/01/2006 to 31/12/2007

2.3 Measured Data Analysis

2.3.1 Average Wind Speed

The wind characterization in terms of speed, direction and wind power is the first step to obtain the initial feasibility of generating electricity from wind power through a wind farm, in a given region. The most critical factor influencing the power developed by a wind energy conversion system is the wind speed. The average wind speed V_m is given as:

$$v_m = \frac{1}{n}\sum_{i=0}^{n} v_i \qquad (1)$$

Where V_i is the wind velocity at each 10-minute interval and n is the number of 10-minute wind data records. The average wind speed is calculated at hourly, daily, monthly and annual interval.

2.3.2 Wind Power Density

The wind power per unit area, P/A or wind power density at interval i is given by:

$$\frac{P}{A} = \frac{1}{2}\rho v_i^3 \qquad (2)$$

Where V_i is 10-minute average wind speed in m/s and ρ is air density. The power density is calculated for each 10-minute average wind speed using above expression and the annual average wind power density is thus the average of the sum of the power density of the 10-minute data. The wind speed and power density at a certain height determines the wind power class of the site. The wind power class of a site is determined as per the standard classification reported in [2].

2.3.3 Wind Shear Coefficient

The wind shear coefficient is calculated assuming power law relationship at the two heights. The coefficient α is found from:

$$\alpha = \frac{\ln(v_2) - \ln(v_1)}{\ln(z_2) - \ln(z_1)} \qquad (3)$$

Where V_1 is the wind speed at height z_1 and V_2 is the wind speed at height z_2.

2.3.4 Turbulence Intensity

The average turbulence intensity of the sites was calculated by taking the average of the individual turbulence intensity values of 10 minute records which were calculated by dividing the standards deviation with the average speed of each record. The turbulence intensity TI of each record is given from [2]:

$$TI = \frac{\sigma}{v} \qquad (4)$$

Where σ is the standard deviation of wind speed and V is wind speed. The overall average turbulence is found in similar way to that shown for wind speed. TI is a relative indicator of turbulence with low levels indicated by values less than or equal to 0.10, moderate levels to 0.25, and high levels greater than 0.25.

2.4 Modeling with WAsP

2.4.1 Observed Wind Climate (OWC)

WAsP (Wind Atlas Analysis and Application Program) was used to generate the Wind Atlas and to develop the wind resource map of the Catchment. The flow modeling of WAsP is discussed in [17]. The various inputs in WAsP modeling are the Observed Wind Climate (OWC) of the site, Vector Map of the study area and Obstacle Groups to the measuring masts. OWC is a tabular summary of the frequency of occurrence of wind speed and wind direction at the measuring site. The OWC is produced from raw wind speed and direction measurements.

The OWC represents the data converted into Weibull probability density function. The Weibull function is defined using two factors namely the scale parameter A and the shape parameter k. The OWC also shows the wind direction distribution as wind rose. Wind rose diagram shows the distribution of wind in different directions. The wind rose diagram is generated by dividing into twelve equally spaced sectors. The frequency distribution for each sector is calculated and plotted in the wind rose diagram.

2.4.2 Generalised Wind Climate (Wind Atlas)

Wind Atlas is a generalized wind climate of the observed wind climate. The data measured from the wind measuring mast is a site specific data. The Wind Atlas data sets are site independent and the wind distributions have been reduced to certain standard conditions. The Wind Atlas contains data for 5 reference roughness lengths (0.000 m, 0.030 m, 0.200 m, 0.400 m, 0.800 m) and 5 reference heights (10 m, 25 m, 50 m, 100 m, 200 m) a.g.l.

2.4.3 Vector Map

Vector maps are used to describe the elevation (orography) and land cover (surface roughness) of the area surrounding calculation sites such as meteorological stations, reference

sites, turbine sites or the sites in a resource grid. WAsP uses vector maps, in which terrain surface elevation is represented by height contours and roughness lengths by roughness change lines. The vector map of the study was prepared from 30 meter resoultion digital elevation model (DEM) downloaded from *ASTER* Global *Digital Elevation Model* GDEM (http://www.gdem.aster.ersdac.or.jp/search.jsp) and Global mapper program was used to create elevation contours at 10-meter interval and export the map in WAsP map format. WAsP Map Editor program was used to edit the map by adding roughness change lines which are manualy created and imported from Google Earth.
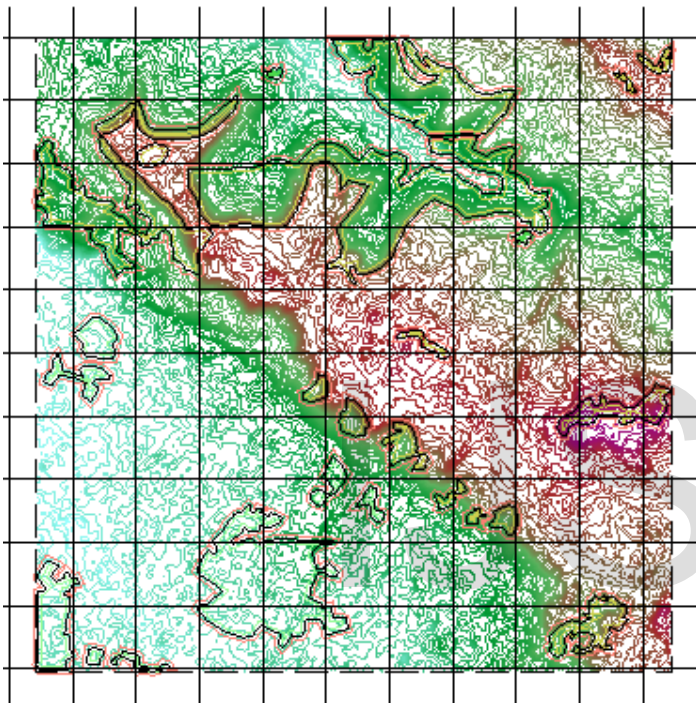

Fig. 3. Vector map of study area showing roughness and height contours

2.4.4 Resource Grid

Resource grid is a rectangular set of points for which summary of predicted wind climate data are calculated. The points are regularly spaced and are arranged into rows and columns. The resource grid is used see a pattern of wind climate or wind resources for an area. Each point in the grid is like a simpler version of a normal turbine site. All the points have the same height a.g.l. If a wind turbine generator is associated with the grid, then that specification is used for all of the points in the grid [17]. For each point in the grid, WAsP calculates the following data which can be displayed in the resource grid: elevation, mean wind speed, mean power density, annual energy production (if a wind turbine generator is associated), Weibull-A value, Weibull-k value, ruggedness index RIX, delta-RIX performance indicator.

3 RESULT AND DISCUSSSION

3.1 Data Screening and Validation

Data screening and validation was conducted as per the procedure discussed in section 2.2. The summary of results of the data screening and validation is shown in Table 2. The data recovery rate was found to be around 98%. Measures were taken to replace the missing and erroneous data records when necessary. During data inspection a large number of consecutive missing data which runs for up to 14 days was observed. There was no measure taken to fill these missing data since it is a large number of data and it is not possible to fill it by average values of the nearby data records. Wind shear coefficient will be negative if the wind speed at 40-meter height is less than wind speed at 10-meter height and it will be undefined when the wind speed at 40-meter height is zero while the wind speed at 10-meter height is greater than zero. The negative and undefined wind shear coefficients were corrected by power law using the average wind shear coefficient calculated based on overall average wind speeds at 10 and 40 meters. Very large wind speed records surrounded by smaller records were inspected. This was corrected by replacing the abnormally large wind speed by the average of the wind speed records just above and below the large wind speed.

Table 1. Data screening and validation

Available Data Records (10-minute average)	103,001
Total number of missing Data Records	2,119
Gross Data Recovery Rate (%)	97.98
Number of Negative and Undefined wind shear coefficients	3,657

3.2 Results of Measured Data Analysis

3.2.1 Average Wind Speed and Power Density

The overall average wind speed and average power density of the data during the period were calculated based on the equations discussed in section 2.3. The results obtained are shown in Table 3. Included in this table is the maximum wind speed recorded averaged in the 10-minute measurement interval. The wind power density class at each height for the respective sites as per the standard classification reported in [2] is also shown in the table.

Table 2. Average wind speed and power density

Average Wind Speed (m/s)		Maximum Wind Speed (m/s)		Average Wind Power Density (m/s)		Wind Power Density Class	
10 m	40 m	10 m	40 m	10 m	40 m	10 m	40 m
5.12	6.41	14.5	18.2	138.55	276.52	II	III

3.2.2 Wind Shear

The wind shear coefficients were calculated based on the overall average wind speeds at 10 and 40 m using power law as per the equation shown in section 2.3.3. The wind shear coefficient was calculated based on the overall mean wind speeds at 10 and 40 meters and was found be be equal to 0.163. The wind shear profile of the site was plotted based on the calculated coefficient as shown in Figure 4.
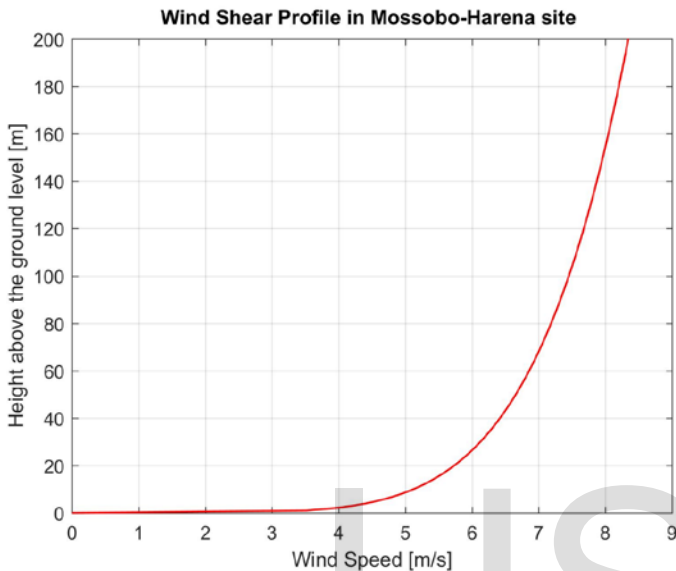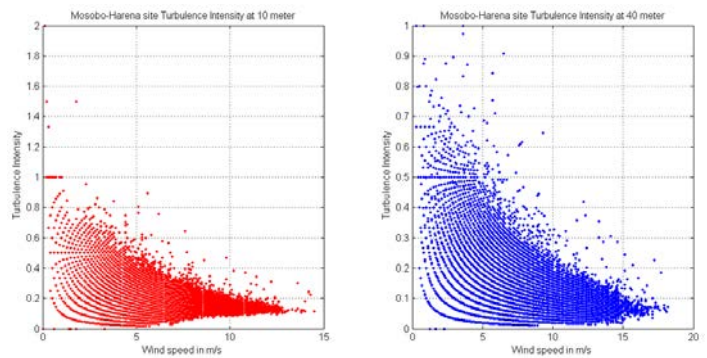
Fig. 5. Turbulence Intensity

3.3 Results of WAsP Modeling and Analysis

3.3.1 Observed Wind Climate (OWC)

Observed wind climate is a tabular summary of the frequency of occurrence of wind speed versus wind direction. The time-series of wind speed and direction data were transformed into a table which describes a time-independent summary of the conditions found at the measuring site using the WAsP software. Figures 6 and 7 show the results OWC of the site at 10 and 40 meter a.g.l.

Fig. 4. Wind shear profile

3.2.3 Turbulence Intensity

The average turbulence intensity was calculated based on the formula discussed in the methodology section 2.3.4. The turbulence intensity of each wind speed record was calculated by dividing the standard deviation of wind speed by the wind sped and the mean turbulence intensity of the site was found by taking the average of the turbulence intensities of individual wind speed records. The results at the two heights is shown in Table 4.

Table 4. Turbulence intensity

Average Turbulence Intensity		Maximum Turbulence Intensity	
10 meter	40 m	10 meter	40 meter
0.176	0.136	2	1

The average Turbulence Intensity is less than 0.25 and greater than 0.1 which indicates the site has moderate turbulence intensity in the sites. As shown in Fig. 5 below the turbulence intensity decreases as wind speed increses as it is the ratio of standard deviation and wind speed.
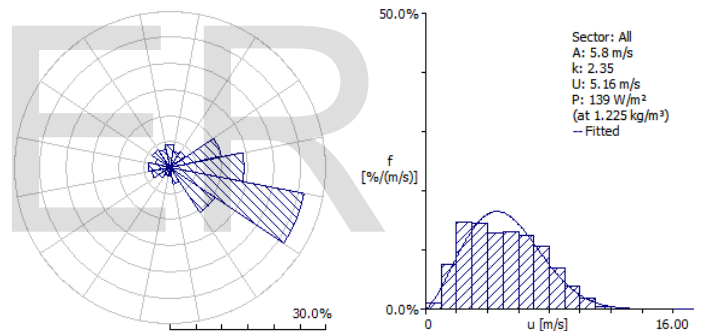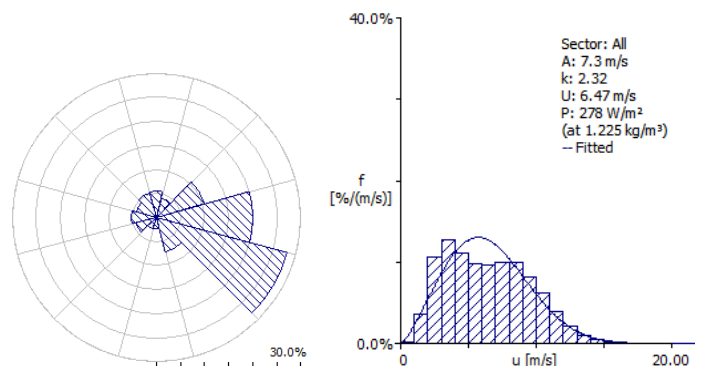
Fig. 6. OWC at 10 m a.g.l.

Fig. 7. OWC at 40 m a.g.l.

As shown in figures 6 and 7 above the OWC result from WAsP has two parts, the wind rose indicating the wind direction distribution and the Weibull function overlaid on the bar chart of the raw data. The Weibull parameters, the average wind speed and power density are also shown on the side of the Weibull function plot. The results shown as OWC were used as an input to determine the Wind Atlas of the site.

3.3.2 Generalized Wind Climate (Wind Atlas)

OWC is site specific data from the measuring mast. Based on the OWC, the generalised wind climate or wind atlas data sets are generated. Wind Atlas data setes are site independent data sets and the wind distributions have been reduced to certain standard conditions. The results are tabulated for the five reference heights and five roughness lengths in terms of the Weibull parameters A and k; average wind speed and power

density. The Wind Atlas contains data for 5 reference roughness lengths (0.000 m, 0.030 m, 0.200 m, 0.400 m, 0.800 m) and 5 reference heights (10 m, 25 m, 50 m, 100 m, 200 m) a.g.l. Table 8 below shows the summary of the generalized wind climate (Wind Atlas data sets) generated using the 40 meter observed wind climate. Wasp version 12.01 used for this study uses new geostrophic wind shear model where the vertical and horizontal extrapolation models are modified to take into account large-scale horizontal temperature gradients ('baroclinic' effects), which induce geostrophic wind shear. The method is implemented by extracting average geostrophic-scale wind shear from global CFSR reanalysis data, with values from the nearest grid points automatically used to provide more accurate AEP predictions.

Table 5. Generalised wind climate summary

Height	Parameter	Roughness length [m]				
		0.03	0.1	0.2	0.4	0.8
10.0 m	Weibull A [m/s]	4.51	3.93	3.53	3.09	2.58
	Weibull k	1.99	2.03	2.05	2.07	2.1
	Mean speed U [m/s]	4	3.48	3.13	2.73	2.29
30.0 m	Weibull A [m/s]	5.64	5.09	4.72	4.3	3.84
	Weibull k	2.13	2.15	2.17	2.19	2.21
	Mean speed U [m/s]	5	4.5	4.18	3.81	3.4
50.0 m	Weibull A [m/s]	6.33	5.75	5.38	4.97	4.51
	Weibull k	2.24	2.26	2.27	2.28	2.31
	Mean speed U [m/s]	5.6	5.1	4.77	4.4	4
70.0 m	Weibull A [m/s]	6.87	6.27	5.89	5.47	5.01
	Weibull k	2.31	2.31	2.32	2.33	2.33
	Mean speed U [m/s]	6.09	5.56	5.22	4.85	4.44
100.0 m	Weibull A [m/s]	7.57	6.92	6.52	6.08	5.6
	Weibull k	2.29	2.3	2.3	2.31	2.31
	Mean speed U [m/s]	6.71	6.13	5.77	5.39	4.9

3.3.3 Wind Turbine Generator selection for Estimation of Annual Energy Production

To ensure an appropriate level of safety and reliability, the environmental parameters shall be taken into account during the selection of appropriate wind turbines.

Wind turbines are grouped into classes according to IEC 61400-1, Rev 3 depending to their ability to withstand defined wind conditions. These classes are characterized by the 10-min average value of the extreme wind speed with a transgression probability once every 50 years and by annual mean wind speed at hub height criteria, the sub classes A, B refer to the turbulence intensity at a wind speed of 15 m/s at hub height.

Wind turbines are divided into four classes with respect to the design wind conditions. The classes are defined by wind speed and turbulence data (Table 6). The wind data forming the basis for the design are characterized by:

- the mean annual wind speed ($\bar{v}_w$)
- the maximum wind speed to be expected as a mean value over 10 min, the so-called reference wind velocity (ve $_{ref}$)
- the so-called characteristic turbulence intensity at a wind speed of 15 m/s (I_{15}).

Within the four classes, the two categories A and B characterise the design for different turbulence conditions. The standard deviation (σ_1) of the longitudinal wind velocity (turbulence) is specified by the parameter a.

Table 6. Basic wind parameters at rotor hub height for wind type classes [11, 12].

WT Classes		I	II	III	IV	S
$v_{e\,ref}$	(m/s)	50	42.5	37.5	30	
$\bar{v}_w$	(m/s)	10	8.5	7.5	6.0	
$v_{G50} = 1.4v_{e\,ref}$		70	59.5	52.5	42	values to be
$v_{G1} = 1.05v_{G50}$		52.5	44.6	39.4	31.5	specified by
A	I_{15}	0.18	0.18	0.18	0.18	the designer
	a	2	2	2	2	
B	I_{15}	0.16	0.16	0.16	0.16	
	a	3	3	3	3	

The wind speed parameters for IEC Wind Turbine classification is given in Table 6. Class I turbines are designed to operate in the harshest climates, with strong annual average wind speeds and turbulent wind. Class II turbines are designed for most typical sites and Class III and IV turbines are designed for low wind resource sites.

The IEC (1999) standard specifies a 'reference wind speed' ve ref which is five times the annual mean wind speed. The 50-year extreme wind speed V_{G50}, is then given by 1.4 times V_{ref} at hub height, and varying with height using a power law exponent of 0.11. The annual extreme wind speed, V_{G1} is taken as 75 percent of the 50-year value [16]. The annual average wind speed of the site at different hub heights can be read extrapolated from the 10-minute average wind speed at 40 meter and using Equation 3 and shear coefficient of 0.163 calculated for determination of wind shear profile.

Table 7. Wind Turbine class at different hub heights

Hub Height	Annual Mean wind speed (m/s)	Reference wind speed (m/s)	50-year extreme wind speed (m/s)	Annual extreme wind speed (m/s)	Suitable Wind Turbine Class for the area
40	6.41	32.05	44.87	33.65	IIIB
60	6.85	34.24	47.94	35.96	IIIB
80	7.18	35.89	50.25	37.69	IIIB
100	7.44	37.22	52.11	39.08	IIIB
120	7.67	38.35	53.69	40.27	IIB
140	7.87	39.33	55.06	41.29	IIB

Wind turbine class III is suitable for the site for hub heights ranging from 40 m to 100 meter and for hub heights from 100 m to 140 m wind turbine class II is suitable.

The average turbulence intensity of Mossobo-Harena site, measured at Mossobo-Harena measuring mast at 40 meter is 13.6%. This leads that Mossobo-Harena site to be classified as IEC wind class IIIB, the lowest wind class meaning that wind turbines of Class III or Class II on the current market can be suitable for development of wind park in the area.

In addition to the wind class of the site, to select appropriate wind turbine for the site the distribution of wind speed, turbulence intensity of the site, the cut-in, rated and cut-out wind speed of the turbine generator, and availability of the turbine in market are taken into consideration. Considering the site's wind resource potential IEC wind turbine Class II or Class III with low cut-in wind speed (2-3 m/s) and rated wind speed (12-13 m/s) and cut-out wind speed of 25 m/s is appropriate for the site. For the purpose of this study, ENERCON E-82 E2 wind turbine generator is selected due to its ability to work effectively in low to medium wind resource sites with low cut-in and rated wind speeds. ENERCON E-82 E2 has a rotor diameter of 82 meter and comes with 78, 84, 85, 98, 108, and 138 different hub-height alternatives.

For the purpose of this study a hub height of 98 meter is selected to maximize the annual energy production of the turbine. During feasibility study of the wind farm project a detail economic analysis and other considerations like topographical conditions on site, turbine availability the Ethiopian market, transportation, foundation work and erection should be done to decide on the hub-height of the turbine from the various alternatives. The E-82 E2 wind turbine has the following basic operational data and power curve.

Table 8. Basic characteristics of ENERCON E-82 E2 wind turbine (at ρ = 1.225 kg/m^3).

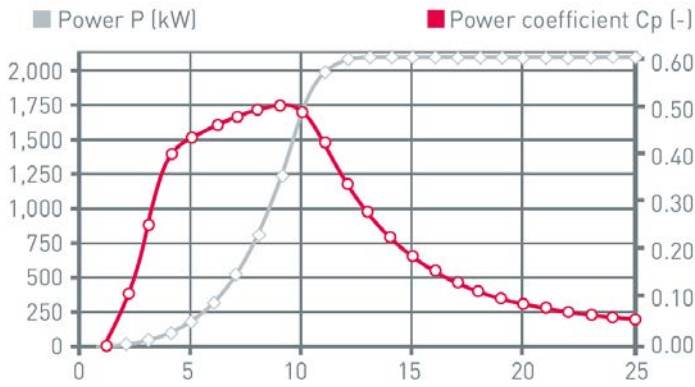|	
Rated Power	2,050 KW
Rotor Diameter	82 m
Hub height in meter	98
Wind zone	WZ III
Wind Class (IEC)	IEC/EN IIA
Cut-in wind speed	2 m/s
Rated wind speed	12.5 m/s
Cut-out wind speed	25.0 m/s
No. of blades	3
Swept area	5,281 m^2

Fig. 8. Power Curve of ENERCON E-82 E

3.3.4 Resource Grid at 98 m a.g.l

WAsP was used to generate the resource grid of the site as defined in section 2.4.4. Inputs required in addition to the Wind Atlas are the vector map, roughness map and obstacle groups around the measurement mast. The software then provided grided maps of the wind speed, power density, annual energy production, Weibull parameters, ruggedness index, change in ruggedness index and other grid results. ENERCON E-82 E2 wind turbine was associated with the resource grid to estimate annual energy. The main results from the resource grid are shown in figures 9 to 11 below.

Table 9. Resource grid setup

Column count	400
Row count	400
Calculation sites	160000
Resolution	25 m
Boundary extent	(550445.5, 1494964) to (560445.5, 1504963.5)
Nodes extent	(550458, 1494976) to (560433, 1504951)
Height a.g.l.	98m
Turbine	ENERCON E-82 E2

3.3.4.1 Resource Grid Results

The overall resource grid statistics at 98 meter above the ground level is shown Table 10. As shown in the table the mean wind speed and power density at 98 meter above ground level is 6.65 m/s and 235 W/m²
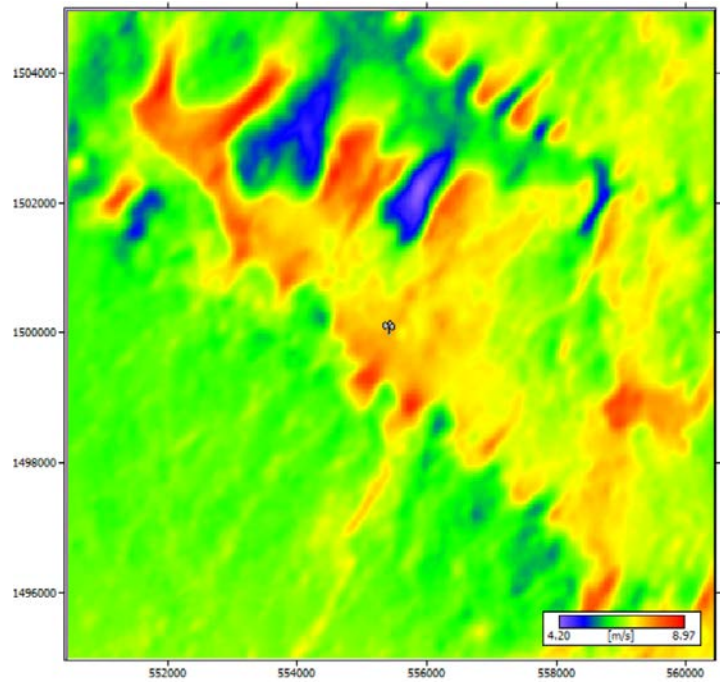
i.   Mean Wind Speed
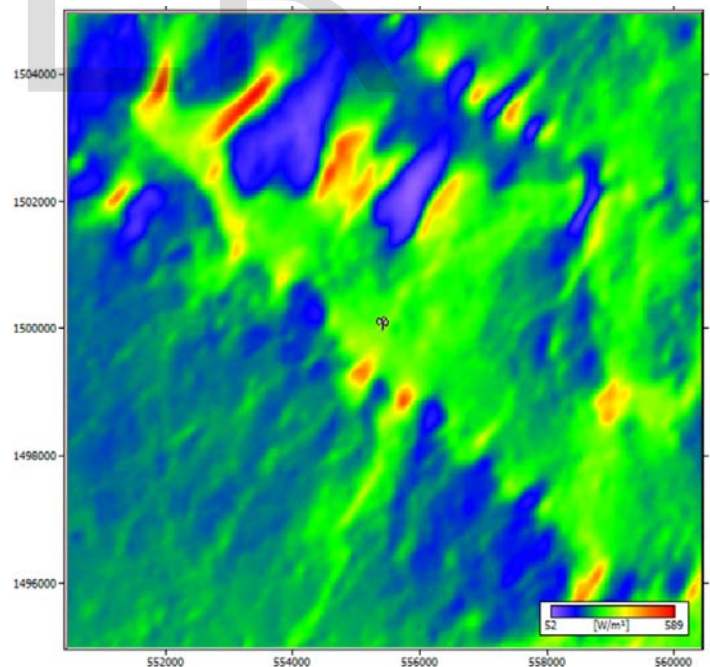

Fig. 9. Mean Wind speed

ii.   Power Density
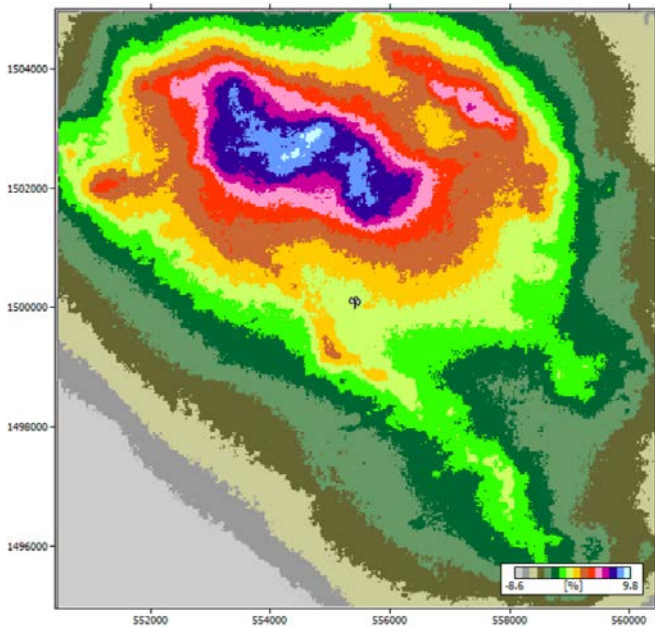

Fig. 10. Power Density

iii.   ΔRIX

Fig. 11. Change in Rugdeness index

The mean annual energy production from the associated EN-ERCON E-82 E2 wind turbine is 4.679 GWh and the maximum and mean change in rugdeness index of the site is 9.8% and -1.80 % respectively.

The relation between the orographic performance indicator, dRIX, and the wind speed prediction error is given in the figure below. The results were obtained from cross-predictions between five metrological stations in complex terrain in northern Portugal. The data shown in the figure is from five Portuguese sites.
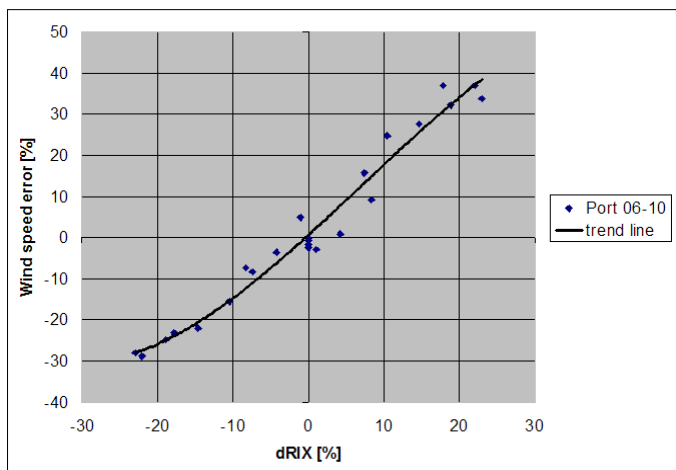
Fig. 12. WAsP wind speed prediction error versus the difference in extent of steep slopes (RIX values) between the predicted and the reference site [17].

As shown in figure 12, as ΔRIX increases the wind speed prediction error is increased. In Mossobo-Harena area the maximum ΔRIX is 9.80%. According to figure 4.34 above a maximum of about 17 percent of wind speed error is expected. The mean value of ΔRIX is -1.8% which results in about 2% overall wind speed prediction error in Mossobo-Harena Area. As shown in Fig. 11 most of the top flat topographical area of the site where the measuring mast is located has a lower change in ruggedness index with respect to the metrological site indicating that the wind speed prediction error in this part of the site is low.

Table 10. Overall resource grid statistics at 98 meter a.g.l

Variable	Mean	Min	Max
Air density	0.925 kg/m³	0.895 kg/m³	0.946 kg/m³
Weibull-A	7.5 m/s	4.7 m/s	10.1 m/s
Weibull-k	2.29	1.86	2.68
Mean speed	6.65 m/s	4.20 m/s	8.97 m/s
Power density	235 W/m²	52 W/m²	589 W/m²
Elevation	2174.1 m	1940.0 m	2530.0 m
RIX	6.80%	0.00%	18.40%
Delta-RIX	-1.80%	-8.60%	9.80%
AEP	4.769 GWh	1.062 GWh	8.320 GWh

3.3.5 Wind Speed and Power Density Maps at 50 m

Wind speed and power density resource grid files at 50 meter above the ground level were exported as surfer grid files and Surfer software were used create the final wind speed and power density maps at 50 meter above the ground level. The wind speed and power density was divided in to the following seven standards which are widely accepted in the wind energy technology. The wind speed and power density resource maps developed by Surfer is shown in figures 13 and 14 below.

Table 11. Wind power density classes [11]

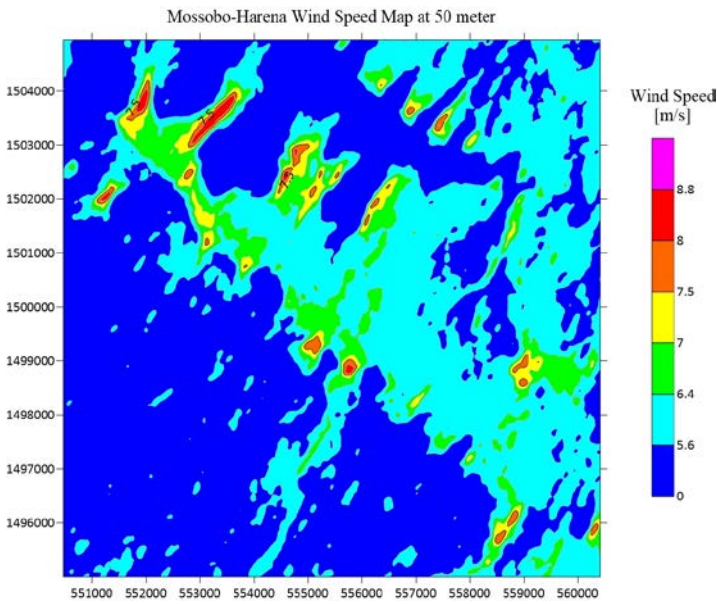| Wind power class	Resource Potential	30 m		50 m	
		Power Density [W/m²]	Speed [m/s]	Power Density [W/m²]	Speed [m/s]
1	Low	0-160	0-5.1	0-200	0-5.6
2	Marginal	160-240	5.1-5.8	200-300	5.6-6.4
3	Fair	240-320	5.8-6.5	300-400	6.4-7.0
4	Good	320-400	6.5-7.0	400-500	7.0-7.5
5	Excellent	400-480	7.0-7.4	500-600	7.5-8.0
6	Out-standing	480-640	7.4-8.2	600-800	8.0-8.8
7	Superb	640-1600	8.2-11.0	800-2000	8.8-11.9

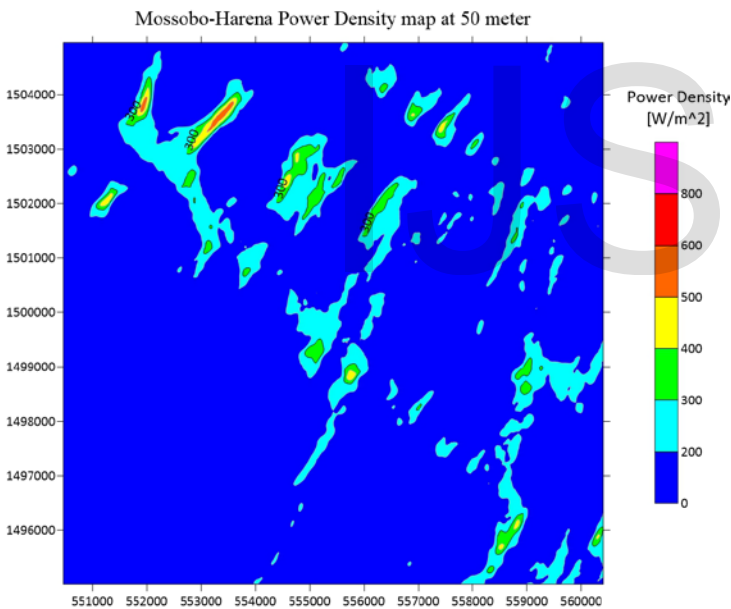Fig. 13. Mossobo-Harena wind speed map at 50 m

Fig. 14. Mossobo-Harena power density map at 50 m.

The color map was done in such a way that the change in color designates change in wind class i.e. Blue (Class 1), Cyan (Class 2), green (class 3), yellow (class 4), orange (class 5), red (class 6) and magenta (class 7). As shown in the figures the majority of the site is covered by class 1 area which is not suitable for wind energy development. The vicinity area of the wind mast is covered mainly by Class 2 and 3 sites can be used for wind energy development using tall turbines. As shown in the wind speed and power density maps developed and the google earth synchronization in Fig. 15 below the Mossobo-Harena

site has a good wind resource potential at the top of the Mossobo-Harena ridge. Wind power density Class II and III sites are suitable for wind farm development by using tall (high hub height) turbines.

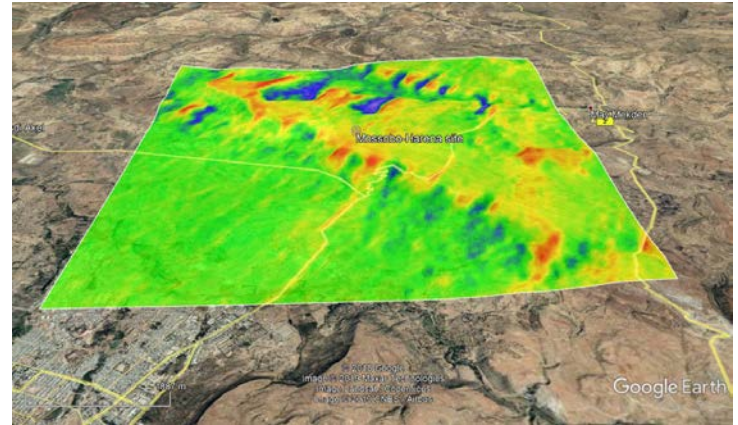### 3.3.6 Google Earth synchronization of Wind Speed Map at 50 m

Fig. 15. Wind Speed Map synchronization with Google Earth

3.4 Wind Farm Modeling and Estimation of Annual Energy Production

3.4.1 Turbine Siting and Wind Farm Layout

A wind farm layout was developed on the study area to estimate the annual energy production. Since the most important factor that should be considered when choosing a wind turbine location is the wind resource potential of the area, the location of turbine sites was chosen based on the wind speed map of the site which had been generated by WAsP.

Sitting of turbines was done only considering energy production potential with minimum wake losses and thus other socio-economic and road accessibility considerations were not considered. Other factors associated with installing WTGs like the suitability of the ground to install WTGs, economic and social factors require a detailed investigation and experience in the field and so many field measurements.

Based on the rule of thumb that is used to design a wind farm layout, turbines in wind farm are usually spaced somewhere between 5 to 9 times the rotor diameters apart in the prevailing wind direction, and between 3 to 5 times the rotor diameters apart in the direction perpendicular to the prevailing winds. The wind turbine selected for this study has a rotor diameter of 82 meters and thus the turbine should be spaced 410 to 738 meters apart in the prevailing wind direction and 246 to 410 meters apart in the direction perpendicular to the prevailing wind direction. Therefore, for this research case turbines are sited with a minimum of 650m of spacing in prevailing wind direction and 400 m of spacing in direction per-

pendicular to prevailing winds so as to optimize annual energy production with minimum wake loss land availability.

In order to simplify the installation, operation, maintenance and for efficient power transmission of the wind park, groups of wind turbines are locally concentrated and installed forming a turbine cluster. A turbine cluster consists of a set of turbine sites which differ from each other in their map location. The proposed wind site has area coverage of 10km x 10km on which a total of 98 turbines were sited.
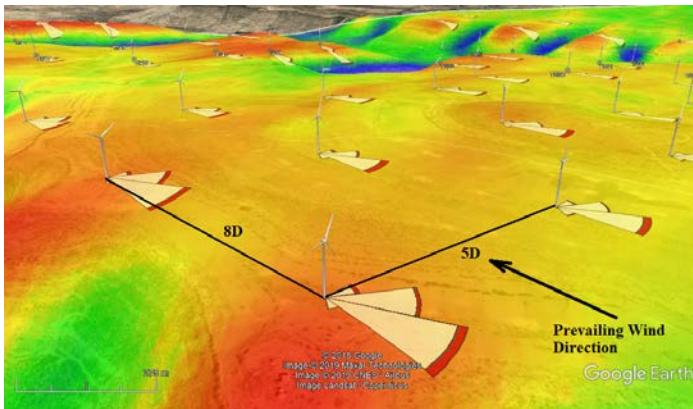
Fig. 16. Siting and spacing of Wind Turbines in the wind farm

The turbine sites were selected using the following points.

- Sites having good mean wind speed were selected by the aid of the wind speed map at 50 meter.
- The Google Earth synchronization of the wind speed map was used to selected turbine sites which are relatively flat (low RIX values).
- The areas were also selected in such a way that it is not situated on towns, villages, roads, water bodies and mountains.
- The turbines were carefully sited with the help of Google Earth synchronization so that the farm produces higher annual energy with minimum wake loss.

3.4.2 Mossobo-Harena Wind Farm Results

3.4.2.1 Site Information and Wake effects modelling

Wake losses are modelled using PARK2 wake model in WasP.

Table 12. Mossobo-Harena Wind farm site information and wake effects modelling

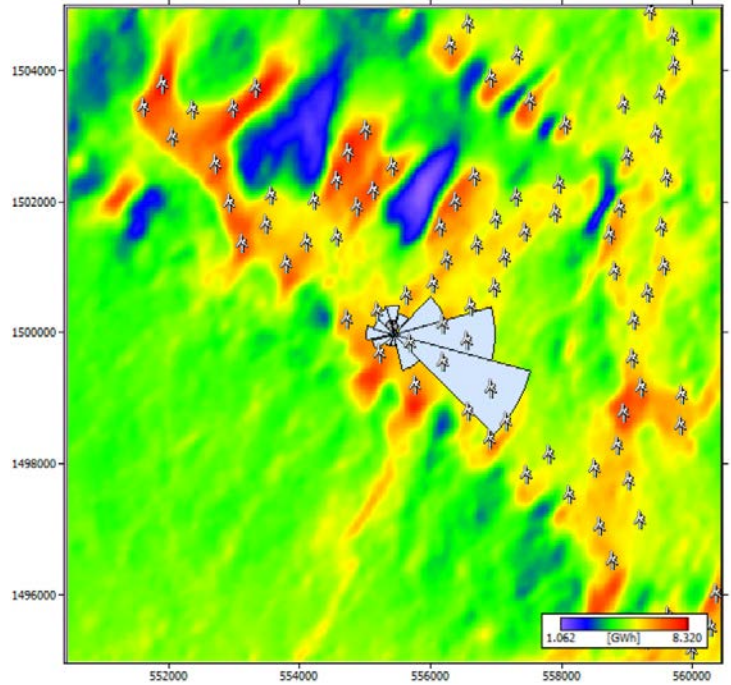| Number of turbines	88
Wind turbine Generator	ENERCON E-82 E2
Uniform hub height a.g. l	98 m
Wake decay constant	0.075

Fig. 17. WAsP resource grid map, showing the AEP potential, layout of the turbines and prevailing wind direction

3.4.2.2 Summary of Wind farm results

Table 13. Summary of results of Mossobo-Harena Wind farm

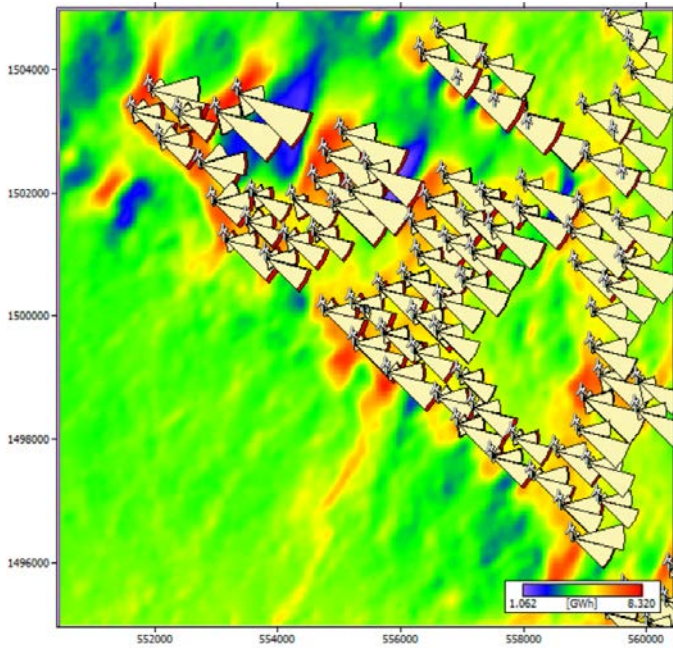| Variable	Total	Mean	Min	Max
Total gross AEP [GWh]	536.789	6.1	5.004	8.139
Total net AEP [GWh]	510.563	5.802	4.6	7.93
Proportional wake loss [%]	4.89	-	0.34	10.16
Mean speed [m/s]	-	7.47	6.81	8.9
Mean speed (wake-reduced) [m/s]	-	7.31	6.59	8.75
Air density [kg/m³]	-	0.912	0.896	0.924
Power density [W/m²]	-	324	242	577
RIX [%]	-	-	2.5	16.5

Fig. 18. Gross AEP and wake loss of turbine sites

3.4.3 Mossobo-Harena Wind Farm Losses and Capacity Factor

The net capacity factor is the ratio of an actual electrical energy output over a given period of time to the maximum possible electrical energy output over that period. The rated power of the selected wind turbine, ENERCON E-82 E2, is 2.05 MW. The rated annual energy production (AEP) of the selected turbine is calculated as

Rated AEP = Rated power x the number of hours in a year
            = 2.050 MW x 8760
            = 17, 957 MWh = 17.957 GWh

Rated AEP of the wind farm = Rated AEP of a turbine x total number of turbines
            = 88 x 17.957 = 1,580.304 GWh

As shown in the wind farm summary result in Table 11 the net AEP of the wind farm is 510.563 GWh. Therefore, the capacity factor (CF) of the farm is

CF = 510.563 GWh/1580.304 GWh
   = 0.323 = 32.3 %

The net annual energy production calculation by WAsP considers only the wind farm wake loss. But in practice there are various other losses occurring along electro mechanical drive which reduce the overall wind farm efficiency. Thus, the total net annual energy production of the farm will be lower the value calculated by WAsP.

In addition to the wake loss the various other losses that occur in a wind farm have following approximate values [12].

1. Wake loss = 4.89 % (Calculated by WAsP)

2. Availability (amount of time for which it is available to operate when maintenance and repair time is taken into account) = 97 %
3. Bearing efficiency = 99.60%
4. Gearbox efficiency = 97.20%
5. Generator efficiency = 96.50%
6. Efficiency of Frequency converter = 97.50%
7. Transformer and other transmission accessories = 98.00%

Therefore, considering the above various losses the net wind farm efficiency would be 80.91%. Then the new actual net AEP is calculated to be 0.8091* 536.789 GWh = 434.315 GWh and therefore the actual CF of the wind farm is

CF = 434.315 GWh/1580.304 GWh
   = 0.2748 = 27.48 %

The usage time or equivalent full-load hours is calculated by dividing the annual energy yield by the turbines' rated power

Usage time = annual energy yield (KWh)/rated power (KW)
           = 434315000 KWh/2050KW * 88 turbines
           = 2407.5 hrs

4 CONCLUSION

In this study wind data from Mossobo-Harena wind measuring mast was collected and analyzed. Wind Atlas Analysis and Application Programme (WAsP) was used to generate Generalised Wind Climate (Wind Atlas) of the area and to develop the wind speed and power density maps of at 50 m above the ground level. The measured data analysis conducted indicates that the mean wind speed at 10 and 40 meters above the ground level is 5.12 m/s and 6.41 m/s respectively at measuring site. The measuring site's mean power density was determined to be 138.55 W/m² and 276.52 W/m² at 10 and 40 meters above the ground level respectively. The prevailing wind direction in the site is from East to South East where about 60 percent of the wind was recorded. The resource grid maps developed by WAsP on 10 km x 10 km area at 50 meter above the ground level indicates that the selected study area has a mean wind speed of 5.58 m/s and mean power density of 146 W/m². The average turbulence intensity of the site was found to be 0.136 at 40 meter which indicatss that the site has moderate level turbulence level. According to the resource assessment done, the area is classified as wind Class IIIB site. ENERCON E-82 E2 wind turbine which is a IEC Class IIB turbine with 82-meter rotor diameter and 98-meter hub height was selected for estimation of annual energy production on the proposed wind farm. 88 ENERCON E-82 E2 wind turbines were properly sited in the wind farm with recommended spacing between the turbines so as so reduce the wake loss. The net annual energy production and capacity factor of the proposed wind farm was determined to be 434.315 GWh and 27.48 % after considering various losses in the wind farm.

5 RECOMMENDATIONS

This study is only a preliminary study in order to estimate the energy potential in the wind farm and does not include environmental, economic and financial issues studies. For a comprehensive study prior to construction and installing wind energy conversion systems, a detail environmental, economic and financial feasibility analysis for the proposed wind farm should be performed. It is recommended that on-site observation be carried out for each wind turbine candidate site separately in order to examine the challenges of individual turbines installation. In this study development of Wind Farm was undertaken by modeling the wind flow at the intended Wind Farm using wind flow modeling tool in WAsP. As a future work the data that has been analyzed using the WAsP tool can be cross checked with the CFD modeling tool for reducing the uncertainties and errors that arise from the WAsP modeling.

6 ACKNOWLEDGEMENT

7 REFERENCES

[1] AWS Scientific, Inc. Wind Resource Assessment Handbook: Fundamentals for Conducting a Successful Monitoring Program [Book]. - Albany: [s.n.], 1997.

[2] Bruce H. Bailey Scott L. McDonald Wind Resource Assessment Handbook: Fundamentals for Conducting a Successful Monitoring Program [Book]. - CESTM, 251 Fuller Road Albany, NY 12203: AWS Scientific, Inc., 1997.

[3] Burton Tony [et al.] Wind Energy Handbook [Book]. - Baffins Lane, Chichester: John Wiley & Sons, Ltd, 2001.

[4] EEP Facts in Brief 2010 E.C [Report]. - 2010 E.C.

[5] energypedia.info Ethiopia Energy Situation [Online] // energypedia.info. - 2018. - 04 02, 2018. - https://energypedia.info/wiki/Ethiopia_Energy_Situation.

[6] European Wind Energy Association (EWEA) Wind Energy-The Facts: A guide to the technology, economics and future of the wind power [Book]. - London: Earthscan, 2009.

[7] GTZ Feasibility Study for Wind Park Development in Ethiopia and Capacity Building [Report]. - 2006. - p. 290.

[8] GTZ Wind Energy programme TERNA-Ethiopia, Wind data evaluation after 12 months [Report]. - 2006.

[9] GWEC Global Wind Report 2016 [Report]. - [s.l.] : Global Wind Energy Council GWEC 2016, 2017.

[10] HYDROCHINA BEIJING ENGINEERING CORPORATION Master Plan Report of Wind and Solar Energy in the Federal Democratic Republic of Ethiopia [Report]. - February 2012.

[11] Manwell J.F., McGowan J.G. and Rogers A.L. Wind Energy Explained: Theory, Design and Application [Book]. - Chichester: John Wiley & Sons Ltd, 2002.

[12] Mathew Sathyajith Wind Energy Fundamentals, Resource Analysis and Economics [Book]. - Berlin: Springer, 2006.

[13] Mortensen Niels G. and Petersen Erik L. INFLUENCE OF TOPOGRAPHICAL INPUT DATA ON THE ACCURACY OF WIND FLOWMODELLING IN COMPLEX TERRAIN [Report]. - Roskilde, Denmark: Risø National Laboratory, 1997.

[14] Robert Y. R., Per D.A. and Poul E.M. Wind Energy in the 21st Century: Economics, Policy, Technology and Changing Electricity Industry [Book]. - London: © UNEP Collaborating Centre on Energy and Environment, 2002.

[15] Tong Wei Wind Power Generation and Wind Turbine Design [Book]. - [s.l.] : WIT Press, 2010.

[16] Tony Burton David Sharpe, Nick Jenkins, Ervin Bossanyi Wind Energy Handbook [Book]. - Baffins Lane, Chichester West Sussex, PO19 1UD, England: John Wiley & Sons, Ltd, 2001.

[17] WAsp 11 WAsp 11 Help Documentation [Report]. - [s.l.]: Risø National Laboratory for Sustainable Energy.