ISSN 2229-5518

Wind Energy Data Analysis and Resource Mapping of East Gojjam Zone, Amhara Region, Ethiopia

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Abstract— Knowledge of wind energy regime is a pre-requisite for any wind energy planning and implementation projects. The wind energy potential of Ethiopia is estimated to be about 10,000MW, but only less than 8 percent of it is utilized so far. One of the reasons for this low utilization of wind energy in Ethiopia is absence of a reliable and accurate wind atlas. Development of reliable and accurate wind atlas 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 project is to analyze the available wind energy data in East Gojjam Zone, Amhara Region, Ethiopia and develop a resource map which could help planners, potential investors and researchers in identifying potential area for wind energy applications in the zone. In this research project wind data collected over a period of two years from Debre Markos and Motta metrological stations was analyzed using different statistical software like Excel, WindRosePRO3 and MATLAB 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 each site were determined. Wind Atlas Analysis and Application Programme (WAsP) was used to generate the wind atlas of the area and to develop the wind speed and power density maps. Appropriate Wind turbines were selected and annual energy production was estimated on selected wind turbine sites in the zone. The measured data analysis conducted indicates that the average wind speeds at 10 meter is about 2.44 m/s in Debre Markos site and 2.41 m/s in Motta site. The mean power density at 10 meters was determined to be 17.82 W/m^2 and 16.20 W/m^2 in Debre Markos and Motta sites respectively. The prevailing wind directions in the zone are North East, South East, South West and North West. The wind resource map developed by WAsP at 50 meters indicated that the zone has mean wind speed and power density of 5.35 m/s and 203 W/m^2 respectively at 50 meter above the ground level. Most of the area of zone is covered by Class 1 sites with power density less than 200 W/m^2, but there are some potential sites in zone with class 2 and 3 sites with mean power density reaching up to 400 W/m^2.

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

1 Introduction

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. 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 electrical energy supply system is from its consists14 hydro power plants, six standby diesel generators, one geothermal and three wind farm power plants with installed capacity of 3,814.20 MW, 99.17 MW, 7.30 MW and 324 MW respectively with a total of capacity of 4,244.67 MW. Ethiopia's current electrical energy supply is mainly from hydropower with 90% of the total installed capacity from hydropower power plants, 8 % from the wind farms and 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].

Due to the fast-economic development of the country in recent years, Ethiopia has been looking for more electrical energy production options to satisfy the high demand of electricity. Wind energy is a good viable option in this regard due to its complementary nature 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).

The main objective of the study reported in this paper was to conduct wind energy resource assessment and develop wind atlas and resource maps in East Gojjam Zone, Amhara Region, Ethiopia.

2 Methodology

2.1 Description of the Study Area

East Gojjam is one of the eleven administrative zones of Amhara Region. Its capital Debre Markos town is located 300 Kms from the country's capital Addis Ababa and 265 kms from the regional capital Bahir Dar extending between 9^0 50′10.69″ N to 11^0 13′48.31″ N degrees latitude and between 37^0 02′46.3″ E to 38^0 31′41.04″ E degrees of longitude. The zone is bordered on the south by the Oromia Region, on the west by West Gojjam zone, on the north by South Gondar zone, and on the east by South Wollo zone. The bend of the Abay River defines the Zone's northern, eastern and southern boundaries. The zone covers an area of 14,344 square kilometers and has perimeter 695.74 kilometers. The elevation of the zone ranges from 785 m above sea level in Abbay gorge to highest point of 4093 m above sea level in the Çoke Mountains. The topography of most of East Gojjam is characterized by mountainous and plain lands, constituting forty-eight and forty percent of the total area respectively. Of the total area of the Zone, 80.73 percent is categorized under däga (high land) and wäyna däga (medium land) [18], [19].

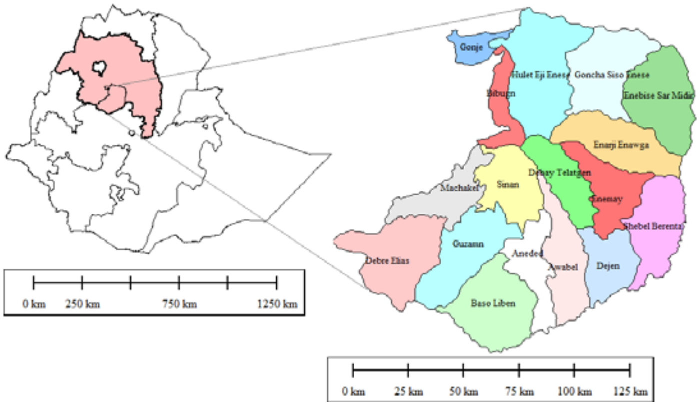

Fig. 1. Map of study area

2.2 Data Collection, Screening and Validation

Wind speed and direction data recorded at a time interval of 15 minutes in Debre Markos and Motta metrological stations 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 15-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. Location of wind measuring masts in the Zone

Description		Measuring Masts	
		Debre Markos	Motta
Location	Latitude	10.32587° N	11.0742° N
	Longitude	37.7395° E	37.8704° E
Altitude above sea level [m]		2458	2413
Height of measuring sensors love ground level [m]		2, 10	2, 10
Available Data Records	From	21/03/2016	21/03/2016
	Until	13/12/2017	20/11/2017

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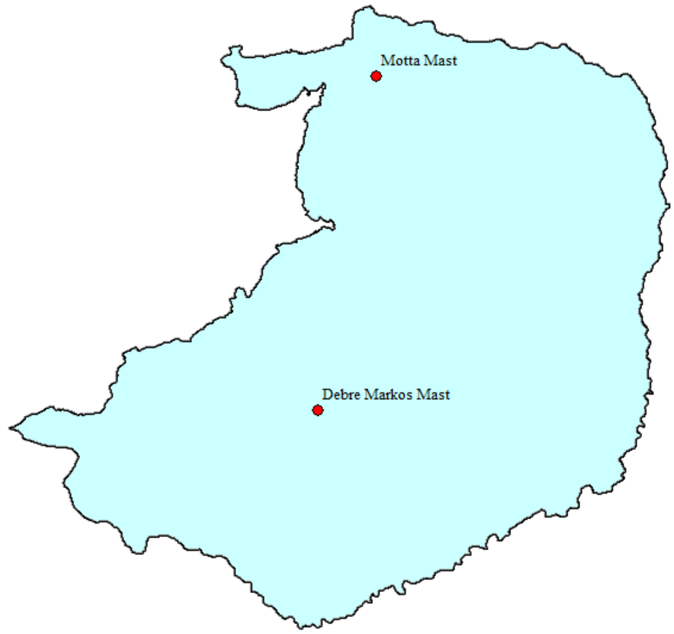


Fig. 2. Wind measuring mast locations in East Gojjam

2.3 Statistical 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 is the wind velocity and n is the number of 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 15-minute average wind speed in m/s and ρ is air density. The power density is calculated for each 15-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 15-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 15 minutes 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 needed in WAsP are Observed Wind Climate (OWC) of sites, 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. 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 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 Resource Map

Resource grid is a rectangular set of points for which summary of predicted wind climate data are calculated. WAsP uses data from one metrological mast to generate Wind Atlas and Resource Grid of an area. However, it doesn't support multiple masts. The area of East Gojjam Zone is too large that it is not recommended to use data from a single mast to generate the Wind Atlas and Resource Grid of the zone. In order to use data from different wind measuring masts the zone was divided in to two areas, Debre Markos area and Motta area, equal to the number of masts. The zone was divided in such a way that each area contains one wind measuring mast as shown in Figure 3. Debre Markos area contains Debre Elias, Guzamn, Machakel, Baso Liben, Aneded, Sinan, Awabel, Dejen, Shebel Berenta, Enemay and Debay Telatgen woreda. Motta area contains Bibugn, Hulet Eji Enese, Enarji Enawga, Enebise Sar Midir, Goncha Siso Enese and Gonje woredas. Wind Atlas and Resource map of each area was generated using observed wind climate of each wind measuring mast and vector map of each area. The wind resource map of the zone was found by the combination of the resource maps of each area.

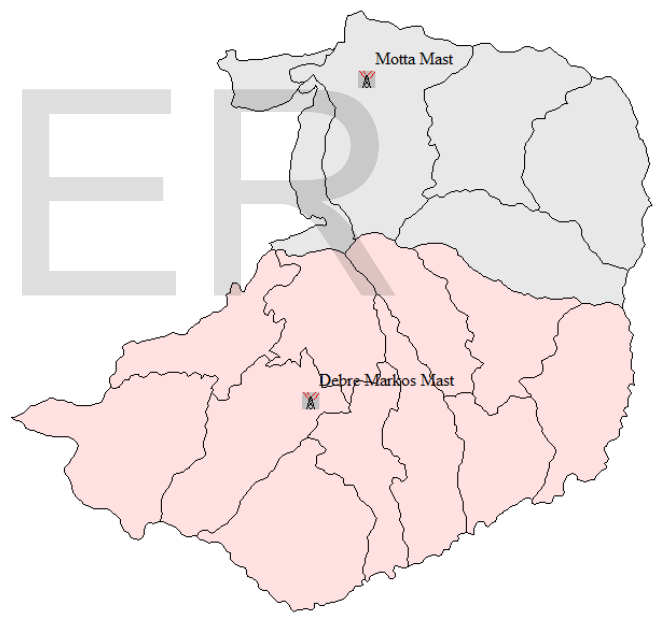


Fig. 3. East Gojjam zone map showing the two divisions of the study area

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 greater than 99% in both measuring stations. Measures were taken to replace the missing and erroneous data records when necessary. A large number of consecutive missing data which runs for up to 6 days was observed in both Debre Markos and Motta sites. There was no measure

ISSN 2229-5518

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. Loss of data also occurred during transfer from data loggers to laptops because the memory card had to be removed. Data lost during transfer of data due to removal of memory card was filled with average data record of the same hour where the data was missing. Wind shear coefficient will be negative if the wind speed at 10-meter height is less than wind speed at 2-meter height and it will be undefined when the wind speed at 10-meter height is zero while the wind speed at 2-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 2 and 10 meters. In both Debre Markos and Motta stations some 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

Description	Measuring measuring station	
	Debre Markos	Motta
Available Data Records (15-minute average)	60,144	57,903
Total number of missing Data Records	551	552
Gross Data Recovery Rate (%)	99.09	99.06
Number of Negative and Undefined wind shear coefficients	2,734	1,919

3.2 Results of Statistical 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 for each site are shown in Table 3. Included in this table is the maximum wind speed recorded averaged in the 15 minutes measurement interval for each site. 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 at the different wind measuring masts

Wind Measuring Mast	Average Wind Speed (m/s)		Average Wind Power Density (W/m^2)		Wind Power Density Class	
	2 m	10 m	2 m	10 m	2 m	10 m
Debre Markos	1.69	2.44	7.79	17.82	I	I
Motta	1.64	2.41	6.05	16.20	I	I

3.2.2 Wind Shear

The wind shear coefficients were calculated based on the overall average wind speeds at 2 and 10 m using power law as per the equation shown in section 2.3. The wind shear coefficient for each site is shown in Table 4. The wind shear profile of the sites was plotted based on the calculated coefficient as shown in Figure 4.

Table 4. Wind shear coefficients

Wind Measuring Site	Wind shear coefficient
Debre Markos	0.18902
Motta	0.23399

3.2.3 Turbulence Intensity

The average turbulence intensity for each site was calculated based on the formula discussed in the methodology section 2.3. The results for each site at the two measurement heights are shown in Table 5.

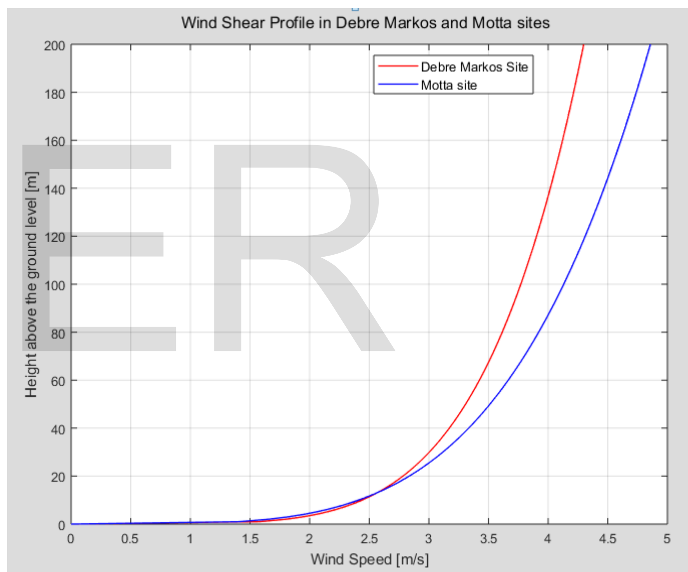


Fig. 4. Wind shear profile

Table 5. Average Turbulence intensity

Wind Measuring Mast	Average Turbulence Intensity	
	2 m	10 m
Debre Markos site	0.698	0.463
Motta site	0.597	0.510

In both Debre Markos and Motta sites the average Turbulence Intensity is greater than 0.25 both at 2 and 10 meters which indicates high turbulence intensity in the sites. The reason for the high turbulence intensity in the sites is the low average wind speed available in the sites. Turbulence intensity decreases at high average wind speeds as it is the ratio of the standard deviation to the average wind speed.

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. Figure 5 shows the results for each site based on the 10 m raw data.

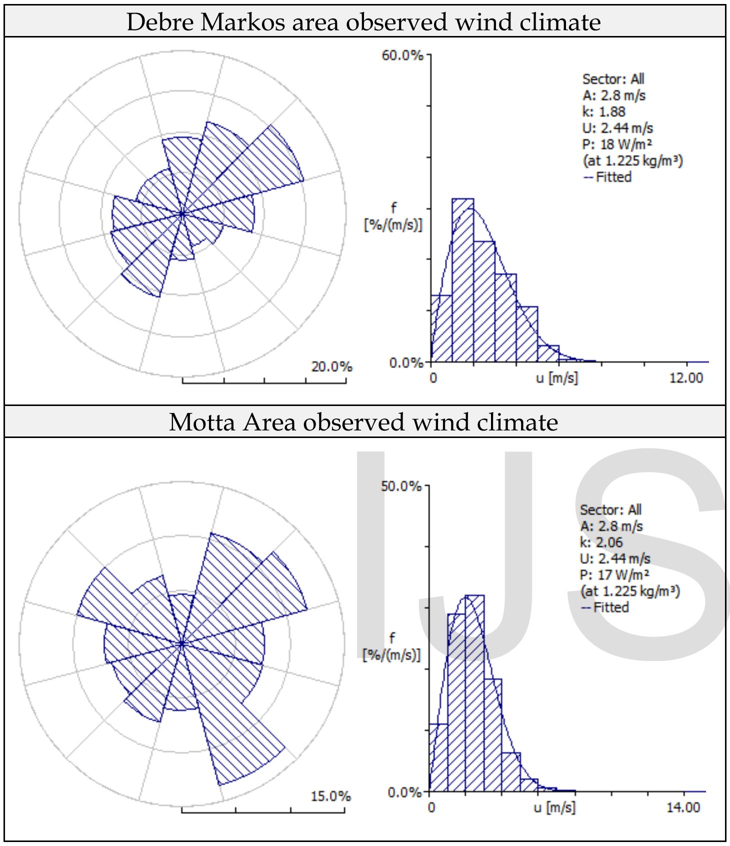


Fig. 5. OWC at measuring masts at 10 m a.g.l.

As shown in figure 5 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 of the sites 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 in each site.

3.3.2 Wind Atlas

Based on the OWC, site independent data sets of the Wind Atlas are found using WAsP software. 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. Table 6 shows the summary of the Wind Atlas data sets for each site.

Table 6. Summary of Wind Atlas

(a) Debre Markos site

H [m]	Parameter	Roughness length (m)				
		0.00	0.03	0.20	0.40	0.80
10	Weibull A [m/s]	5.7	4.1	3.1	2.7	2.3
	Weibull k	2.14	1.91	1.91	1.91	1.92
	Mean speed [m/s]	5.08	3.61	2.79	2.43	2.02
	Power density [W/m²]	144	58	27	18	10
25	Weibull A [m/s]	6.3	4.9	4.0	3.6	3.2
	Weibull k	2.20	2.04	2.02	2.02	2.02
	Mean speed [m/s]	5.57	4.31	3.54	3.20	2.82
	Power density [W/m²]	185	92	51	38	26
50	Weibull A [m/s]	6.8	5.6	4.7	4.4	3.9
	Weibull k	2.25	2.24	2.19	2.17	2.16
	Mean speed [m/s]	5.98	4.99	4.20	3.87	3.50
	Power density [W/m²]	225	131	80	63	46
100	Weibull A [m/s]	7.3	6.7	5.7	5.3	4.8
	Weibull k	2.20	2.37	2.39	2.41	2.42
	Mean speed [m/s]	6.48	5.90	5.04	4.68	4.30
	Power density [W/m²]	291	206	128	102	79
200	Weibull A [m/s]	8.0	8.1	6.9	6.5	6.0
	Weibull k	2.13	2.29	2.32	2.33	2.35
	Mean speed [m/s]	7.10	7.21	6.16	5.75	5.31
	Power density [W/m²]	394	387	239	193	152

(b) Motta site

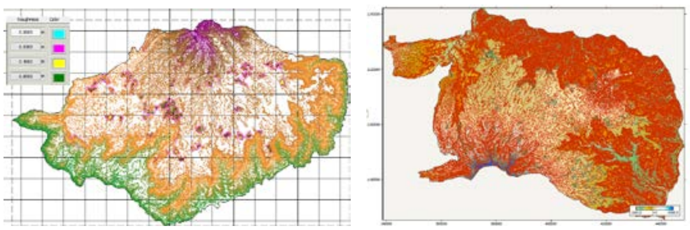
H [m]	Parameter	Roughness length (m)				
		0.00	0.03	0.20	0.40	0.80
10	Weibull A [m/s]	6.4	4.5	3.5	3.0	2.5
	Weibull k	1.87	1.72	1.72	1.72	1.72
	Mean speed [m/s]	5.67	4.03	3.12	2.71	2.25
	Power density [W/m²]	229	91	42	28	16
25	Weibull A [m/s]	7.0	5.4	4.4	4.0	3.5
	Weibull k	1.91	1.81	1.80	1.79	1.79
	Mean speed [m/s]	6.20	4.81	3.95	3.57	3.14
	Power density [W/m²]	293	145	81	60	41
50	Weibull A [m/s]	7.5	6.3	5.3	4.9	4.4
	Weibull k	1.95	1.96	1.93	1.91	1.90
	Mean speed [m/s]	6.66	5.55	4.69	4.31	3.89
	Power density [W/m²]	354	205	125	98	72
100	Weibull A [m/s]	8.1	7.4	6.3	5.9	5.4
	Weibull k	1.92	2.07	2.09	2.10	2.10
	Mean speed [m/s]	7.20	6.54	5.60	5.21	4.77
	Power density [W/m²]	454	316	197	158	121
200	Weibull A [m/s]	8.9	9.0	7.7	7.2	6.6
	Weibull k	1.88	2.04	2.06	2.06	2.06
	Mean speed [m/s]	7.86	7.95	6.82	6.36	5.88
	Power density [W/m²]	607	575	361	293	231

ISSN 2229-5518

3.3.3 East Gojjam Zone Resource Grid at 50 m

WAsP software was employed to plot the resource grid of each zone as defined in section 2.4. Inputs required in addition to the Wind Atlas are the vector map, roughness map and obstacle groups around the measurement mast. All the above required data were prepared for each zone carefully. The software then provided maps of the wind speed, power density and ruggedness index. The input vector maps of the two sites is shown in Figure 6 (a) and maps of the ruggedness index, the wind speed and power density are shown in Figure 5 (b), (c), and (d) respectively. Table 7 shows a summary of the resource grid analysis for the two sites.

(a)



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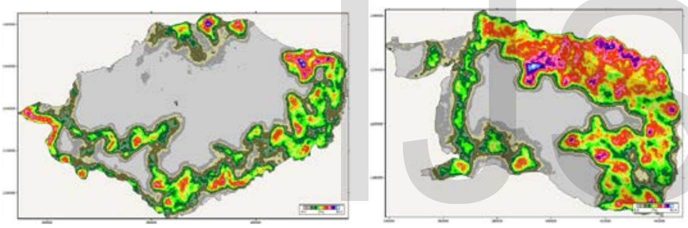

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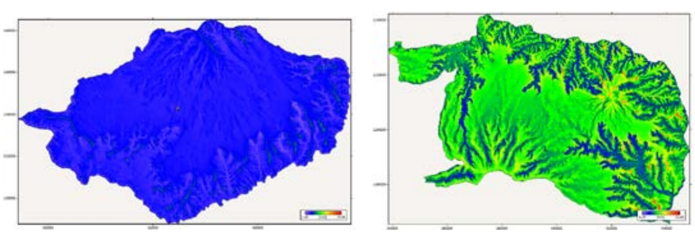

(d)

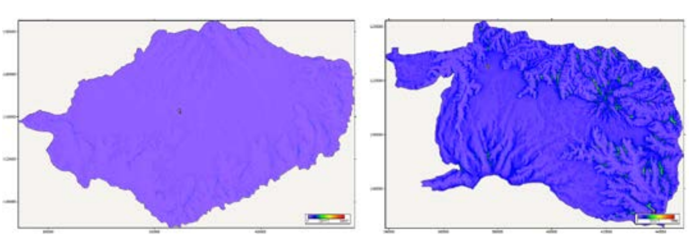

Fig. 6. East Gojjam zone resource grid analyses, (a) vector map (b) ruggedness index (c) wind speed (d) power density.

Table 7. East Gojjam zone wind resource grid overall grid statistics at 50 meters a.g.l

Description	Measuring measuring station	
	Debre Markos	Motta
Mean speed [m/s]	5.05	5.66
Power Density [W/m2]	151	256
Weibull-A [m/s]	5.7	6.4
Weibull-K	2.18	1.88
RIX [%]	6.50	13.50
ΔRIX [%]	6.20	13.0

3.3.4 East Gojjam zone Wind Speed and Power Density Maps at 50 m

Wind speed resource grid files of each site were exported and combined to get the wind speed map and power density maps of East Gojjam Zone. Surfer and ArcGIS software were used for combination of the separate site maps to get the final wind speed and power density maps shown in Figures 7 and 8 respectively.

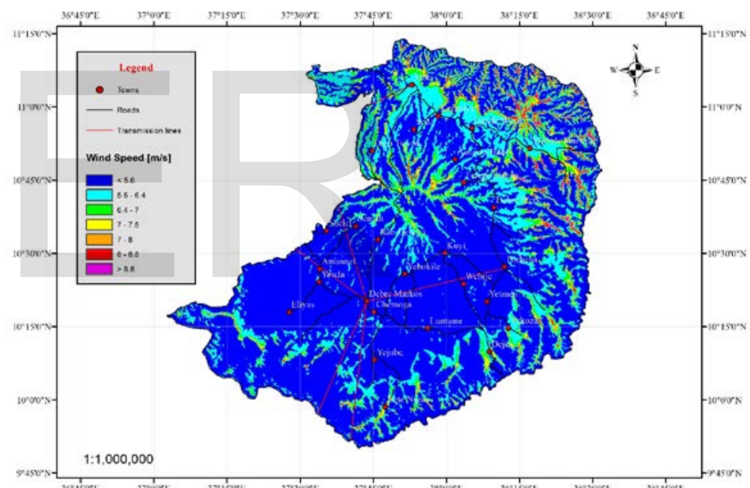

Fig. 7. East Gojjam Zone wind speed map at 50 m.

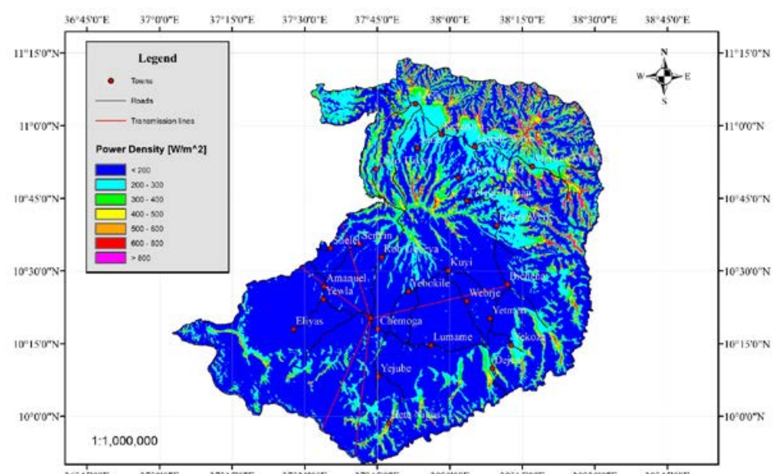

Fig. 8. East Gojjam Zone power density map at 50 m.

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 zone is covered by mainly class 1 sites which is not suitable for wind energy development. Some areas of the zone have class 2 and 3 sites which can be used for wind energy development using tall turbines.

4 CONCLUSION

Wind data from two wind measuring masts in East Gojjam zone was collected and analyzed. Wind Atlas Analysis and Application Programme (WAsP) was used to generate the Wind Atlas of the area and to develop the wind speed and power density maps of the catchment at 50 m above the ground level. The measured data analysis conducted indicates that the average wind speeds at 10 meter is about 2.44 m/s in Debre Markos site and 2.41 m/s in Motta site. The mean power density at 10 meters was determined to be 17.82 W/m² and 16.20 W/m² in Debre Markos and Motta sites respectively. The wind resource map developed by WAsP at 50 meters indicated that the zone has mean wind speed and power density of 5.35 m/s and 203 W/m² respectively at 50 meter above the ground level. Most of the area of zone is covered by Class 1 sites with power density less than 200 W/m², but there are some potential sites in zone with class 2 and 3 sites with mean power density reaching up to 400 W/m².

5 ACKNOWLEDGEMENT

The authors would like to thank Debre Markos University, Institute of Technology for providing the fund required for successful completion of this research.

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