Analysis of Wind Energy Conversion Systems in Two Selected Sites in Libya Using Levelized Cost of Electricity (LCOE)

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Abstract-- **In this paper the wind speed characteristics and energy potential study has been performed taking into account data from the on-site measurement station (mast-height 40m), which is being operated since October 2006. The data collected over a period of two years were evaluated in order to figure out the average wind speed, directions, and the Weibull distribution which included calculations of scale and shape factors for two sites. After that selecting wind turbine class, forecast site wind energy & power density, estimating farm annual energy production (AEP) and the expected cost of electricity. The energy output analysis is done using a wind energy conversion system (WECS) from different manufactures with a rated capacities spectrum from 600 kW to 2400 kW. The study is performed for 50 MW installed capacity wind farms at Misslata and Tarhuna in Libya. Then the monthly and annual energy output, as well as capacity factor over the lifetime of the project (20 years) were determined. The analysis also included a comparison of the energy produced from both sites. The annual energy produced has been found 154 and 166 GWh for Misallatha and Tarhuna which is equivalent to capacity factor of 36.1% and 39.0% respectively. The lowest LCOE are found for both sites as 4.6 and 4.97 c$/kWh. It is clear that Misallatha and Tarhuna are feasible sites to develop a wind farm projects in terms of economic parameters.**

Index Terms—**Wind energy, Sites assessment, Energy evaluation, Levelized cost of energy (LCOE).**

1. INTRODUCTION

The history of using wind energy goes back to over 2000 years was used to pump water and grind grains, while wind turbines in its present form appeared late in 1800 in Denmark specifically the year 1890 to produce electricity. The world's first wind turbine has been installed with the megawatt size in 1941. However, a blade failed problem after 1100-hour operation, there would not be another wind turbine of this size deployed for over 40 years. This goes until the end of the 20th century and early 21st century where the interest to wind turbines started again strongly motivated by the rising of oil and gas prices in one side and climate changes on the other side. As a result, the amount of energy produced from wind power increased dramatically and rapidly [1].

The relationship between energy consumption and environment pollution has become clear due to the negative results such as high levels of carbon dioxide and climate change. During the latter years of the 20th century, the climate change was heavily observed and a more efficient usage of energy was recommended as one of the main areas for improvement to create a cleaner environment. One of the most powerful initiatives in the world to create an environment containing a long-term sustainable production of electricity is the massive wind power development.

Electric power industry known specifically as one of the industries that could be used to reduce carbon emissions by increasing the percentage of electricity from renewable sources such as wind power. This will lead to reduce the dependence on fossil fuels, which in turn will ensure economic stability. Libyan electric power generation system is totally dependent on hydrocarbon resources. The problem of power shedding that the country faces is due to lack of energy resource mix. Therefore, to explore the opportunity for wider energy mix, wind energy will be one possible options. Since the country has enormous potential wind energy is an attractive renewable option for the Libyan energy generation system.

One of the initial steps in planning and building a wind power plant or a wind farm is to consider the wind potential on site. The wind potential is the theoretical amount of energy that the wind contains, measured in the unit watts per square meter (W/m^2) [2]. There is a strong need for the wind power industry to know how much wind energy a site contains. Therefore, as far as wind energy is concerned, the very crucial thing is its potential based on wind speed as well as its direction and the situation of the degree of variation with a given location for a given period of time. The available wind resource is basically governed by the site topographical and weather conditions. It has also a large variability from one location to the other, and also from season to season at any fixed location and makes it possible to decide whether a project will succeed economically or not.

North Africa region is considered as one of the most important areas, which is expected to be very effective for generating electricity from wind energy. The wind power industry grows constantly in Morocco, Egypt and Tunisia which have taken significant steps towards the exploitation of wind generated electricity. A recent report from the Global Wind Energy Council (GWEC) indicates that by the end of 2015 the total installed capacity of wind power in Morocco, Egypt and Tunisia reached 787, 610, and 245

MW respectively, while Libya was not even among the list of the countries that are using wind power [3].

The Ministry of electricity and Renewable Energy Authority of Libya (REAOL) who had prepared a preliminary plan for renewable energy contribution. This Renewable Energy Master Plan is based on renewable energy technologies that are currently available and commercially viable such as wind energy. Based on this plan, a number of proposed projects within the ambitious plan to exploit the available sources of renewable energy in a number of areas with different capacities by using wind and solar power technologies include Derna wind farm project and Misallatha wind farm project of a total capacity of 60 MW.

The study aims to analyze and investigate the available wind resources and energy potential in two selected locations in west of Libya using wind speed data that collected over a period of two years. In this study a detailed resource data analysis is presented. The wind resources at two sites (Misallatha and Tarhuna) are analyzed by using Excel and SAM software issued by the national renewable energy laboratory NREL [4]. The wind farm electrical productivity for every hour throughout the whole a year for both candidate sites is calculated. The annual average wind speeds at 80 m are 7.74 m/s and 8.1 m/s. Both sites have mean power density of 477 W/m^2 and 561 W/m^2 respectively. Accordingly, these sites have been characterized as wind class III according to the IEC regulations. A 2 x 50 MW wind energy power plants is proposed in Misallatha and Tarhuna respectively. The supposed wind farm with 56 turbines having 82 m rotor diameter and 100 m hub height has been analyzed and evaluated. As per this preliminary analysis the farms, the amount of monthly and annual energy production that can be generated from wind farm has been determined. The calculation of the wake losses of the wind turbines causing the so called shadowing effect between the wind turbines has been carried out using the wake model PARK which is part of the SAM software.

Finally, an economic analysis for the development of the wind farm based on the results of wind resource assessment were performed. Essential economic data are considered based on international practices for Wind turbines plants and taking into considerations real figures extracted from proposals submitted to, and evaluated by, local authorities. The lowest electricity production costs are predicted.

2. Measured Wind Speed Data

The wind data used in this study was obtained from Renewable Energy Authority of Libya (REAOL), from measuring stations located at the two proposed sites, Misallatha and Tarhuna in west of Libya [5] as indicated in Fig. 1. REAOL has installed 26 wind measuring stations in different places measure wind speed and direction at different altitudes (40 and 60m tower heights) to determine the most appropriate places for wind farms. The design of these measuring stations are based on the requirements of the IEC standard 61400-12-2 (IEC, 2008). This should ensure the load-bearing capacity of the results achieved and the reproducibility of the measurements carried out.

Fig. 1. Location of the 2 meteorological stations in the northwest of Libya. Misallatha site at 66 km southeast of Tripoli. Tarhuna site at 60 km southeast of Tripoli. Google Earth image of the nearby areas.

Wind data in the form of wind speed and direction as well as temperature, humidity and atmospheric pressure in addition to the data storage unit were measured using a cup-type anemometer and a weathercock were sampled every five seconds at 10 m, 20 m, and 40 m above ground level during two years (October 2006-November 2008). These data were then combined with the standard deviations of the wind data and averaged and stored every ten minutes by the Wind Data logger. During these 10 minutes averaging periods a binary file is generated and held on the data plug. These binary files were later combined with a site file and converted into an ASCII text file using its software.

The geographical coordinates of the meteorological stations used in this study are listed in Table I. Care has been taken during the collection of data to avoid uncertainties and followed the methodologies proposed and explained in the ISO guide (International Standards Organization 1992). The data set has been filtered and all errors values are removed. In addition, wind speeds below the so-called Calm limit (0.2 m/s) were considered separately. The calm limit is defined as the wind speed limit, under which all wind speeds are classified as slow down quickly, since an accurate measurement in these ranges is not possible with all anemometers. However, it cannot be assigned to any particular wind direction, so the mean value has been formed from all wind speeds less than 0.2 m/s and this is distributed equally to all sectors [6].

TABLE I

Information of selected locations

Name	Location				
	UTM X	UTM Y	Datum	Altitude	Period (years)
MISALLATHA	392993	3608787	ED79(33 S)	366 m	2006-2008
TARHUNA	364760	3589581	EU1979 (33 S)	505 m	2006-2008

Long term measurements are needed for a good wind energy assessment. The longer the period of collected data the more reliable are the estimated wind potentials. However, as one year data is sufficient to predict the long-term trend of seasonal mean wind speed to within an accuracy of 10 % and a confidence level of 90 % [7], [8], [9], and [10].

3. Speed Frequency Distribution and Site Weibull Parameters

When planning for installations of wind turbines, it is very important to know the wind conditions on site to optimize plants and to determine the expected energy yields. The statistical distribution of the wind velocities changes from Place to place and depends on (i) local climatic conditions, (ii) the landscape and the (iii) ground surface from. It's not sufficient to consider only the average annual wind speed, because higher wind speeds, have a greater impact on the energy that can be extracted from the wind than the low wind speeds. Therefore, a more differentiated statement about the wind conditions at a location can be obtained via the frequency distribution of the wind speed. Known distribution functions from the statistics are in the field of wind power the WEIBULL distribution, as well as the RAYLEIGH distribution [11]. In Weibull distribution, the variation in wind velocity is characterized by two parameter functions: the probability density function and the cumulative distribution. The probability density function $f(V)$ as in (1) indicates the probability of the wind at a given velocity V, while the corresponding cumulative distribution function $F(V)$ in (2) of the velocity V gives the probability that the wind velocity is equal to or lower than V, or within a given wind speed range:

$$f(V) = \left(\frac{k}{c}\right)\left(\frac{V}{c}\right)^{k-1} e^{-\left(\frac{V}{c}\right)^{k}} \tag{1}$$

$$F(V) = 1 - e^{-\left(\frac{V}{c}\right)^{k}} \tag{2}$$

Where c is the scale factor defines the mean wind speed to a specific wind turbine location in m/s. The Weibull k parameter, which is also referred to as a shape factor, defines the prevailing wind conditions at the site and assumes values between one and three. It thus describes the form of the frequency distribution approximated by the Weibull distribution. Both parameters are determined by the wind speed values measured over a period of two years. Sites with constant or even wind conditions have a k-parameter near the three and thus have a very sharp Weibull curve. Locations with strongly variable wind conditions in the form of frequent droughts and booms require a shallow Weibull curve with a small k-value near the one. The monthly and annual values of Weibull parameters were calculated using least squares method.

In addition to the mean wind speed, the other two significant wind speeds for wind energy estimation are the most probable wind speed (V_F) and the wind speed carrying maximum energy (V_E). They can be expressed respectively as in (3) and (4) [12]:

$$V_F = c\left(\frac{k-1}{k}\right)^{1/k} \tag{3}$$

$$V_E = c\left(\frac{k+2}{k}\right)^{1/k} \tag{4}$$

The most probable wind speed corresponds to the peak of the probability density function, while the wind speed carrying maximum energy can be used to estimate the wind turbine design or rated wind speed. Prior studies have shown that wind turbine system operates most efficiently at its rated wind speed. Therefore, it is required that the rated wind speed and the wind speed carrying maximum energy should be as close as possible [13].

4. Results and Discussion

In this section, the wind analysis results for measured and Weibull distributions of both wind mast sites are presented where evaluation of frequency distribution and wind power as well as energy density were computed. It is also done the turbine selection as per IEC standard to estimate annual energy production, capacity factor, and Levelized Cost of Energy (LCOE) with selected turbine types.

In Figs. 2 and 3 histograms of the wind speed observations are shown at the selected sites with fitted Weibull frequency function and cumulative distribution function derived from the long term wind velocity data at the hub height of 80 m. A histogram (bar graph) showing the number of occurrences of the velocities for both locations in Misallatha and Tarhuna are presented in Fig. 2 and Fig. 3. These histograms were derived from one year of hourly data, for which the mean speed were 7.74 m/s for Misallatha and 8.1 m/s for Tarhuna site. From Fig. 2 it is observed that, the most frequent maximum wind speed in Misallatha is 8 m/s while is 6 m/s in Tarhuna site as demonstrated in Fig. 3. The annual cumulative frequency distribution for two sites indicate that the wind speeds are less than or equal 4 m/s and 7 m/s for less than 14% and 47% respectively of the time during the year at Misallatha and less than 13% and 44% respectively of the time during the year at Tarhuna site. Annual Weibull distribution functions also are showed in Figs. 2 and 3. The shape factor k is 2.31 and 2.25 respectively. As shown in Fig. 4 which compares the two sites in one diagram, as the value of k increases, the curve has a sharper peak, indicating that there is less wind speed variation (a steadier, less variable wind). The cumulative probability distributions of the wind speed at both locations show a similar trend. For wind speeds greater or equal to 4 m/s cut-in wind speed, Misallatha and Tarhuna have frequencies of about 94% and 93.5% respectively as shown in Fig. 4. If a wind turbine system with a design cut-in wind speed of 3 m/s is used in these sites for wind energy resource for electricity generation, both sites will have frequencies of more than 98%.

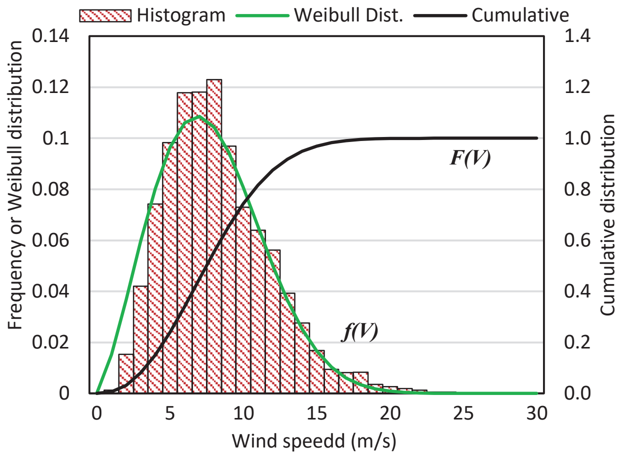

Fig. 2. Comparison of wind histogram, cumulative distribution, and Weibull distribution of Misallatha site.

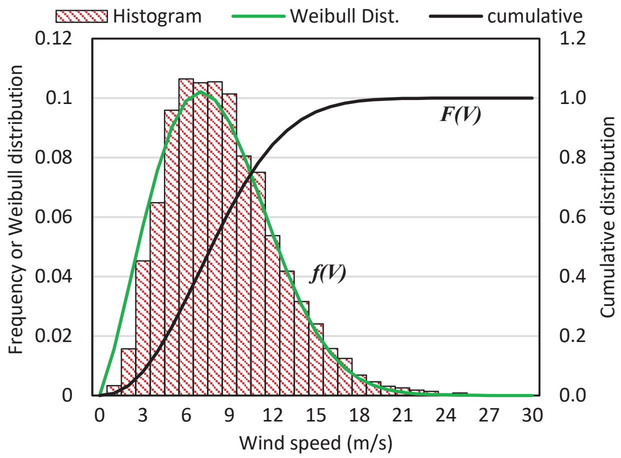

Fig. 3. Comparison of wind histogram, cumulative distribution, and Weibull distribution of Tarhuna site.

Figure 5 shows the plots of the one-hour average wind speeds against time for one month (May 2007). It shows the variations of the wind characteristics about their mean values and how they spread from their mean values.

The directional distribution of the wind resource is a key factor affecting the design of a wind project. In most projects, the spacing between turbines along the principle wind direction is much greater than the spacing perpendicular to it. This configuration maximizes the density of wind turbines while keeping wake interference between the turbines, and hence energy losses, manageable. The wind rose the wind recording of both sites Site of one year are shown in Fig. 6. It can be seen here that for Misallatha site, the majority of the wind direction is concentrated around the south (S) and south-east (SE) directions, such as, about 2400 hours are blown from the south direction and the rest of time is almost uniformly distributed on the other directions.

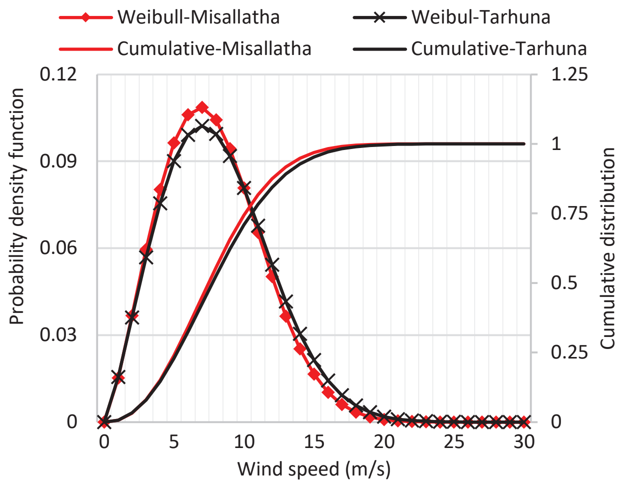

Fig. 4. Comparison of Weibull and cumulative distribution of two sites.

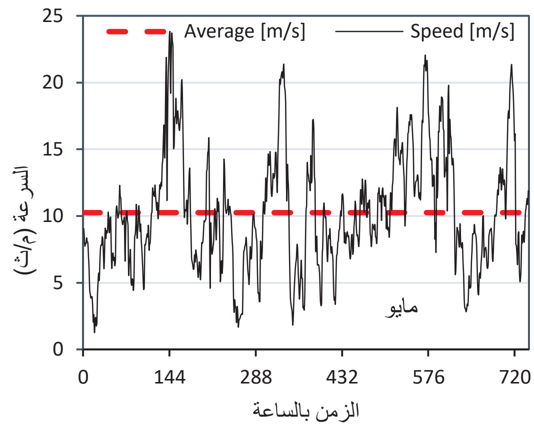

Fig. 5. Instantaneous wind speed recorded at 40 m height for the site of Misallatha during May.

For Tarhuna site, the majority of the wind direction is concentrated between the south (S) and south-east (SE) directions, such as, about 3100 hours are blown between south and south-east, and between north-west (NW) and west (W) directions, such as, about 3300 hours are blown from the north-west to the west direction. There is almost no speed from the directions south-east and north-east of the mast site, and the rest as represented in the Fig. 6 (Left).

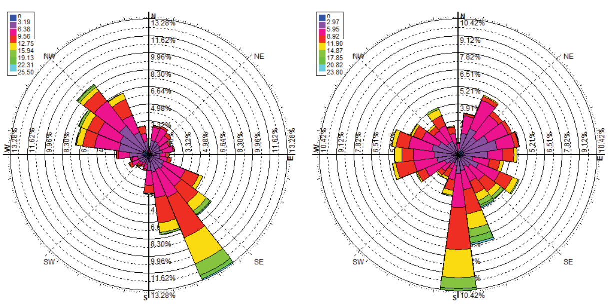

Fig. 6. Wind rose of one year for both locations, Tarhuna (Left), and Misallatha (Right).

With knowledge of the frequency distribution of the wind speeds, a theoretical energy yield can now be determined by taking into account the performance curve of a wind turbine. Figures 7 and 8 show the distribution which represents the probability of the wind speed, power curve of Vestas-100-1.8, and the resulting energy produced. The total annual energy yield is then determined by adding up the individual class year energy yields.

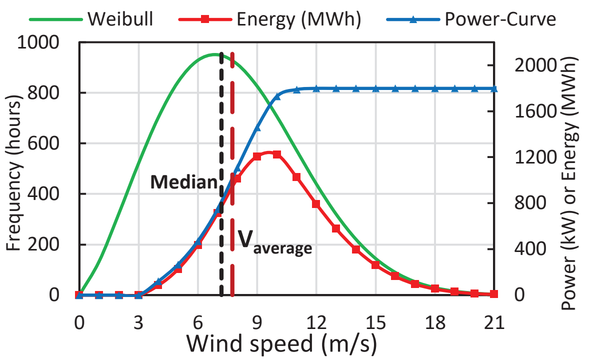

Fig. 7. Weibull distribution for Misallatha with the shape factor k= 2.31 and the scaling factor c = 8.75 m / s, power curve of Vestas 100-1.8 wind turbine at 80 m hub height and energy density produced.

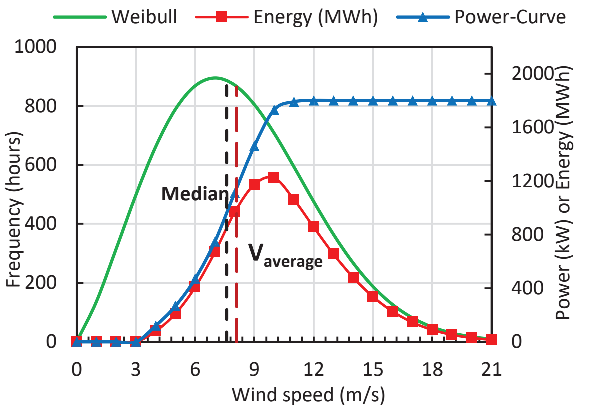

Fig. 8. Weibull distribution for Tarhuna with the shape factor k=2.25 and the scaling factor c = 9.11 m / s, power curve of Vestas 100-1.8 wind turbine and energy density produced.

The monthly variation of the mean wind speed characteristics (V_{avg}, V_F and V_E), mean power density and mean energy density as well as the annual values of these parameters at a height of 80 m are presented in Tables II and III. For Misallatha site, the monthly mean wind speed varies between 5.94 m/s in August and 10.26 m/s in May. The monthly mean power density varies between 184 W/m^2 in August and 1071 W/m^2 in May. In the case the Tarhuna site, the monthly mean wind speed varies between 6.14 m/s in January and 11.4 m/s in June. The monthly mean power density varies between 233 W/m^2 in also January and 950 W/m^2 in June.

Velocity and power duration curves can be useful when comparing the energy potential of candidate wind sites [14]. The velocity duration curve is a graph with wind speed on the y axis and the number of hours in the year for which the speed equals or exceeds each particular value on the x axis as demonstrated in Fig. 9. The total area under the curve is a measure of the average wind speed. In addition, the flatter the curve, the more constant are the wind speeds. The steeper the curve, the more variable is the wind regime.

TABLE II

Main characteristics of Misallatha site at a height of 80 m

	V_{avg} (m/s)	c (c/m)	k	V_F (m/s)	V_E (m/s)	P (W/m^2)	E (kWh/m^2)
Jan	7.448	8.400	2.462	6.798	10.694	405.5	301.7
Feb	6.869	7.780	2.110	5.738	10.671	367.8	247.1
Mar	8.388	9.450	2.600	7.841	11.769	555.4	413.2
Apr	8.297	9.378	2.270	7.261	12.389	605.1	435.6
May	10.260	11.582	2.445	9.340	14.789	1071.5	797.2
Jun	8.523	9.573	2.805	8.181	11.598	555.7	400.0
Jul	6.499	7.355	2.262	5.683	9.733	297.5	221.3
Aug	5.943	6.671	2.890	5.759	8.002	185.0	137.6
Sep	6.901	7.742	2.954	6.731	9.223	201.3	144.9
Oct	7.740	8.719	2.639	7.279	10.798	432.9	322.1
Nov	8.036	9.098	2.274	7.051	12.008	556.9	401.0
Dec	7.961	8.986	2.452	7.258	11.460	499.0	371.2
Annual	7.74	8.752	2.314	6.853	11.45	477.8	4193

TABLE III

Main characteristics of Tarhuna site at a height of 80 m

	V_{avg} (m/s)	c (c/m)	k	V_F (m/s)	V_E (m/s)	P (W/m^2)	E (kWh/m^2)
Jan	6.14	6.94	2.44	5.59	8.88	233.1	173.4
Feb	7.42	8.37	1.78	5.28	12.76	569.1	382.4
Mar	6.49	7.34	2.18	5.54	9.89	295.9	220.2
Apr	8.76	9.91	1.98	6.94	14.10	822.1	591.9
May	8.32	9.42	2.33	7.40	12.29	596.2	443.61
Jun	11.4	12.79	2.81	10.93	15.48	1319.7	950.2
Jul	8.26	9.33	2.46	7.55	11.87	559.4	416.2
Aug	9.0	10.12	2.88	8.73	12.15	645.9	480.5
Sep	7.0	7.85	2.88	6.77	9.42	301.5	217.1
Oct	7.75	8.70	2.76	7.39	10.60	419.2	311.9
Nov	7.71	8.68	2.68	7.30	10.69	423.3	304.8
Dec	8.48	9.54	2.71	8.05	11.69	558.0	415.1
Annual	8.0	9.11	2.247	7.01	12.09	561.0	4907

A power duration curve of both sites are shown in Fig. 10. The difference between the energy potential of both sites (Misallatha and Tarhuna) is visually apparent, because the areas under the curves are proportional to the annual energy available from the wind.

5. ENERGY PRODUCTION FROM A WIND FARM OF 50 MW INSTALLED CAPACITY

The calculations of the expected annual energy yield of the proposed wind farms at Misallatha and Tarhuna sites, which are based on the two years measured wind data, are done using a self-programmed Microsoft Excel sheets and SAM program considering the Vestas-100-1.8 wind turbine of 1.8 MW. The wind park array losses, turbine availability, electrical losses, and Miscellaneous losses were considered. The selection of the wind turbine is done under the consideration of the IEC Standard and parameters resulted from the site data analysis which are: (i) Annual mean wind speed (ii) power density (iii) Wind speed for maximum occurrence energy generation (iv) Maximum frequently occurred wind speed (v) Cut-in and cut-out wind speed. This leads Misallatha and Tarhuna sites to be classified as IEC wind class III, meaning that nearly every wind turbine on the current market is suitable for both sites wind park in terms of wind class. The resulting energy yield in both locations is displayed in Table IV. A parametric run simulation involves assigning wind turbines types as input variable to explore the dependence of a Levelized cost of energy (LCOE) as an output is performed. The total number of simulated wind turbines in parametric simulation was 40 wind turbine. As a result of simulation, the minimum LCOE (optimum wind turbine) for both sites was Vestas-100-1.8 wind turbine, Fig. 11. Table V gives a List of the best selected turbines for both sites according to the minimum LCOE.

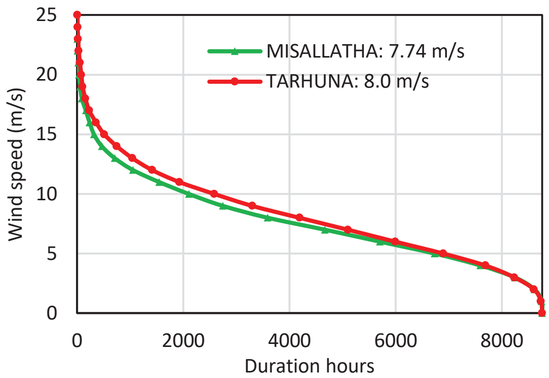

Fig. 9. Velocity duration curve.

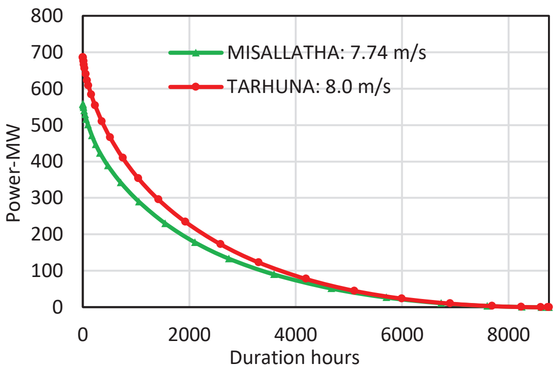

Fig. 10. Power duration curve.

6. ECONOMIC ANALYSIS

The economic analysis has been conducted in the form of calculating LCOE for several types of wind turbines by using the specific cost of installation per kW. A supposed wind farms each having 27 wind turbines with 100 m rotor diameter at 80 m hub height has been subjected to an economy analysis by assuming capital costs (CAPEX) of 1800 $/kW and cost of operation and maintenance (OPEX) of 60 $/kW-year. The annual energy production is 154 GWh for Misallatha and 166 GWh for Tarhuna site as indicated in Table IV, which is equivalent to a capacity factor of 36.1 and 39.0%. The Levelized Cost of Energy (LCOE) for Misallatha and Tarhuna are $49.7 and $46.0/MWh respectively. These values of production and cost are apparently enough to think in both sites as a feasible site to develop a wind farm projects.

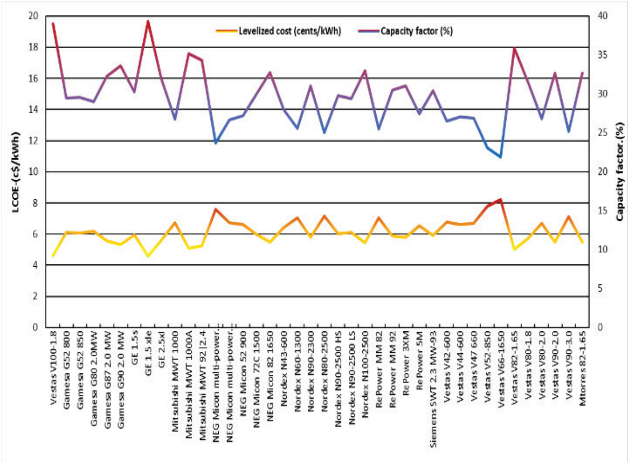

Fig. 11. Levelized cos of electricity and capacity factors for Tarhuna site by using several types of wind turbines.

TABLE IV

Summary of main estimation result for the different scenarios

Description	MISALLATHA	TARHUNA
Type of Turbine	Vestas V100-1.8	Vestas V100-1.8
Turbine Capacity [kW]	1800	1800
Number of WTG [-]	27	27
Installed park capacity [kW]	100,000	100,000
Hub Height [m]	80	80
Rotor Diameter [m]	100	100
Specific Rotor Area [m2/kW]	4.36	4.36
Wind park array losses [%]	11.5	11.5
Turbine availability [%]	90	90
Electrical losses [%]	6.8	6.8
Miscellaneous losses [%]	2.0	2.0
Net Output [MWh/y]	153,660	166,066
Specific Energy Production [kWh/y/m^2]	725	783
Full load hours [h/a]	3150	3400
Capacity Factor [%]	36.1	39.0
LCOE [c$/kWh]	4.97	4.60

TABLE V

List of the best selected turbines according to LCOE for Tarhuna

Wind Turbine	Power (kW)	Rotor Diameter (m)	LCOE[a] (c$/kWh)	LCOE[b] (c$/kWh)
Vestas V100-1.8	1800	100	4.97	4.60
GE 1.5 xle	1500	82.5	4.97	4.60
Vestas V82-1.65	1650	82	5.43	5.00
Mitsubishi MWT 1000A	1000	61.4	5.65	5.10
Mitsubishi MWT 92|2.4	2400	92	5.76	5.23
Gamesa G90 2.0 MW	2000	90	5.86	5.34
Nordex N100-2500	2500	100	5.96	5.44
NEG Micon 82 1650	1650	82	6.01	5.48

[a] Misallatha, [b] Tarhuna

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