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Assessment of Wind Power Potential at Hawksbay, Karachi Sindh, Pakistan

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Abstract

Pakistan is facing serious energy crisis at present. The government is aiming to utilize the immense potential of renewable energy sources like: Solar, Wind, etc, in addition to intensify the conventional sources of energy to over the acute shortage of energy. Wind energy is the fastest-developing energy source worldwide. The aim of this paper is to explore and estimate the wind power potential of Hawksbay Karachi, one of the locations in southern part of Pakistan. Wind speed data (in meters per second) from April 2009 to April 2011 at four different heights is measured. Wind power densities, frequency distribution, and Weibull distribution of wind speed are calculated in this study. This study also presents the analysis and comparison of 5 numerical methods to determine the Weibull scale and shape parameters for the available wind data. The estimated wind power to be generated through commercial wind turbine is also included. The yearly mean wind speed at Hawksbay, Karachi is 5.9m/s and has power density of 197W/m^2 at 80m height with high power density during April to August. The estimated cost per kWh is US$0.0345. Therefore the site may be considered suitable for wind turbine applications.

Keywords: *Wind energy, Power density function, Weibull distribution, Rayleigh Distribution, Capacity factor*

1. Introduction

The economic and social stability of any country strongly depends upon the availability of energy. The per capita energy consumption is an index used to measure the prosperity of any society. Pakistan is a developing country with population of almost 177 million people has average yearly energy consumption of about 450kWh per capita, whereas the world's is about 2730kWh [1]. Pakistan is basically an energy deficient country. Almost 37% people amongst the population living in remote and rural areas are waiting to be connected to the national grid.

The country's installed electricity generation capacity at present is approximately 19,566MW, 30% of which is from hydel, 67% from fossil fuels (32.3% from natural gas and 35.3% from oil in 2008-09) and remaining from nuclear energy [2-4]. The contribution of hydroelectricity in the total generation of the country has been declining gradually from 70% in the 1960s to 33% at present [5]. This trend has triggered a massive raise in electricity price as well as increased air pollution.

Country's poor economy does not allow spending billions of dollars on fossil fuel imports, particularly oil. Most of the imported oil is used for electricity generation. The country's limited internal gas and oil base, with their existing production rate, will get exhaust within 2 to 3 decades. Pakistan's immense coal potential has not been potentially utilized due many reasons. Similarly technology barriers, high cost, and international restrictions are the big barriers in developing nuclear energy [6]. Thus an immediate search for cost-effective, sustainable and environment-friendly energy sources is necessary to meet the country's requirements. Renewable-energy resources particularly wind energy technology is rapidly growing energy resource throughout the world because of its ample existence, reduced cost and having low environmental damage [7]. The wind power generation capacity of the world has reached to 196,630MW by the end of 2010 [8].

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In order to explore the wind potential, Pakistan Meteorological Department (PMD) and Alternative Energy Development Board (AEDB) in co-ordination with UNDP has gathered wind data in coastal areas of Pakistan. Wind data collected at Hawksbay, Karachi is presented in this paper. Assessments and evaluations of wind energy potential are performed by many countries of the world [9-15].

The aim of this article is to highlight the potential of wind resource at Hawksbay, Karachi at the coast of Sindh. Data collected at the site has been analyzed, estimated power available in the wind and electrical power expected to be generated via commercial wind turbine has also been calculated in order to support the evaluation and planning of future wind energy projects in southern region of Pakistan.

2. Wind Assessment and Data Analysis

It is essential to have the familiarity with wind characteristics like; speed, duration of time that wind is available and direction in order to investigate the wind energy potential for a certain location. Besides, the density of air, design of turbine and the turbine tower height affect the power generated from the wind. These characteristic will be discussed in the subsequent sections.

2.1 Wind Speed Characterization

The speed of wind varies with height. Several functions can be used to express this variation. The power exponent function is commonly used function and is given in following equation;

$$V(z) = V_r \left(\frac{Z}{Z_r} \right)^{\beta} \tag{1}$$

where $V(z)$ is speed of wind at height Z agl (above ground level), V_r is speed of wind at reference height Z_r agl and β is an exponent, relies on surface roughness length. The length of surface roughness and β for various types of terrains are given in literature [16].

2.2 Statistical Distribution for Wind Data

Wind speed changes with time at particular location therefore it is necessary to carryout empirical determination of wind speed distribution. Weibull and Rayleigh distributions are two of the more often used functions among a number of available empirical functions to fit wind data over period of time at particular location.

2.3.1 Weibull Distribution Function

The Weibull distribution function offers the best agreement with a variety of experimental data analyzed [17-20]. It has widely been used for the assessment of wind potential for different regions in many countries [5, 13, 21-23]. The Weibull probability density function (PDF) of the wind speed can be determined from the following equation [24-26]:

$$f(V) = \left(\frac{k}{C} \right) \left(\frac{V}{C} \right)^{k-1} \exp\left(-\frac{V}{C} \right)^{k} \tag{2}$$

where C & k are Weibull scale (having no unit) & Shape (same unit as of wind speed; m/s) parameters respectively.

The corresponding cumulative distribution function $F(V)$ can be writing as follow:

$$F(V) = 1 - \exp\left(-\frac{V}{C} \right)^{k} \tag{3}$$

2.3.2 Rayleigh Distribution Function

The Rayleigh distribution is also used extensively for fitting wind speed data. When the value of shape parameter *k=2* the Weibull distribution becomes Rayleigh Distribution. Therefore, the Rayleigh distribution is said to be a one-parameter Weibull distribution. The probability density and respective cumulative distribution functions for Rayleigh distribution can be written as;

$$f(V) = \frac{\pi}{2}\left(\frac{V}{V_{avg}^2}\right)\exp\left[-\left(\frac{\pi}{4}\right)\left(\frac{V}{V_{avg}}\right)^2\right] \quad (4)$$

$$F(V) = 1 - \exp\left[-\left(\frac{\pi}{4}\right)\left(\frac{V}{V_{avg}}\right)^2\right] \quad (5)$$

where V_{avg} is average wind speed which can be found from the following equations;

$$V_{avg} = \frac{1}{N}\left(\sum_{i=1}^{N} V_i\right) \quad (6)$$

The Weibull distribution with two parameters is generally more versatile while the Rayleigh distribution, having one parameter, is simpler to use. Even sometimes the Rayleigh distribution provides a better fitting than the Weibull distribution for fitting the measured probability density distribution [19, 27]. I have been observed that the Rayleigh distribution is biased towards low wind speeds.

2.3 Methods for Determining the Weibull Parameter

Weibull parameters can be determined by using different parameter estimation method. The Weibull distribution is important for the assessment of the wind energy potential and wind characteristics; therefore, it is necessary to find its parameters properly. If its parameters are obtained well, the Weibull distribution not only agree better with wind speed data, but also represent the wind power potential much more accurately [28].
Several techniques are described in the text to determine the Weibull parameters to fit Weibull distribution to the measured data at a certain location. Some of these methods, which provide easy, effective and accurate method for determination of Weibull parameters, are described below;

2.3.1 Graphical Method:

This method is implemented using the concept of least squares to fit straight line to wind data, where the time-series data must be sorted into bins. In this method, the shape "*k*" and scale "*C*" parameter can be determined by re-arranging and taking natural log of cumulative Weibull distribution function, given in equation (3), which yields;

$$\ln\left[-\ln\left(1 - F(V)\right)\right] = k\ln V - k\ln C \quad (7)$$

This is similar to linear equation $y = ax + b$ in which;

$$y = \ln\left[-\ln\left(1 - F(V)\right)\right],\ x = \ln V,\ a = k \text{ and } b = -k\ln C \quad (8)$$

Here *x* and *y* are calculated through the measured wind speed data. The slope *a* and the intercept *b* can be determined through standard least square regression method. Finally, the scale and shape parameters can be calculated as;

$$k = a \text{ and } C = e^{-\frac{b}{k}} \quad (9)$$

2.3.2 Empirical Method:

In this method the Weibull scale '*k*' and shape '*C*' parameter can be determined using average wind speed and standard deviation as follows [29-30];

$$k = \left(\frac{\sigma}{V_{avg}} \right)^{-1.086} \tag{10}$$

$$C = \frac{V_{avg}}{\Gamma\left(1 + \frac{1}{k}\right)} \tag{11}$$

where σ is standard deviation which can be found from the following equations;

$$\sigma = \left[\frac{1}{N-1} \sum_{i-1}^{N} \left(V_i - V_{avg} \right)^2 \right]^{1/2} \tag{12}$$

2.3.3 Maximum Likelihood Estimation Method:

This method is commonly used to determine the Weibull parameters. The shape parameter can be estimated by following equation iteratively [18, 29-30];

$$k = \left(\frac{\sum_{i=1}^{N} V_i^k \ln(V_i)}{\sum_{i=1}^{N} V_i^k} - \frac{\sum_{i=1}^{N} \ln(Vi)}{N} \right)^{-1} \tag{13}$$

where *N* is the total number of wind speed measurements and V_i is the measured wind speed value for the *i*th measurement. After calculating the value of shape parameter *k*, the scale parameter *C* can be determined using following equation;

$$C = \left(\frac{1}{N} \sum_{i=1}^{N} V_i^k \right)^{\frac{1}{k}} \tag{14}$$

2.3.4 Modified Maximum Likelihood Estimation Method:

The modified maximum likelihood method can be considered if wind speed data is available in frequency distribution format. The Weibull parameters are calculated as follows [18, 29-31];

$$k = \left(\frac{\sum_{i=1}^{N} V_i^k \ln(V_i) f(V_i)}{\sum_{i=1}^{N} V_i^k f(V_i)} - \frac{\sum_{i=1}^{N} \ln(Vi) f(V_i)}{f(V \geq 0)} \right)^{-1} \tag{15}$$

where V_i is the wind speed central to bin *i*. $f(V_i)$ the frequency for wind speed ranging within bin *i*, and $f(V \geq 0)$ is the probability for wind speed equal to or exceeding zero.

2.3.5 Energy Pattern Factor Method:

The energy pattern factor method is related to the averaged data of wind speed and is defined by the following equations [29-30, 32];

$$E_{pf} = \frac{(V^3)_{avg}}{(V_{avg})^3} \quad (16)$$

$$k = 1 + \frac{3.69}{\left(E_{pf}\right)^2} \quad (17)$$

where E_{pf} is the energy pattern factor.
The scale parameter can be estimated using equation (11).

2.4 Prediction Performance of Weibull Distribution Model

The correlation coefficient R^2 and root mean square error (*RMSE*) analysis have been carried out in order to determine which one of the Weibull parameter calculation methods gives a better result. These parameters can be calculated from the following equations [29, 33];

$$R^2 = \frac{\sum_{i=1}^{N}\left(y_i - z\right)^2 - \sum_{i=1}^{N}\left(x_i - z\right)^2}{\sum_{i=1}^{N}\left(y_i - z\right)^2} \quad (18)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(y_i - x_i\right)^2\right]^{1/2} \quad (19)$$

where y_i is the *ith* actual data, x_i is the *ith* predicted data with the Weibull distribution, z is the mean of actual data and *N* is the number of observations. The high R^2 and low value of *RMSE* will give the better model.

2.5 Wind Power Generation

The wind power P (W), with air density ρ (Kg/m3), and wind turbine swept area A_T(m²) can be calculated by [34];

$$P = \frac{1}{2}\rho C_p A_T V^3 \quad (20)$$

where C_p is Betz limit and is equal to 0.593

The wind power expressed in terms of area, independent of the wind turbine area, is known as wind power density (*WPD*). It can be obtained from the equation (20), as given below;

$$WPD = \frac{P}{A_T} = \frac{1}{2}\rho C_p V^3 \quad (21)$$

The wind energy (E) extracted by a wind turbine, can be determined as [24];

$$E = T\int_0^\infty P\left(V\right).f\left(V\right)dV \quad (22)$$

where T is time period and $P(V)$ is the wind turbine's power curve

Substitute equation (2) into (22), the wind energy in terms of Weibull distribution is obtained, and is given by;

$$E = T\int\left(\frac{K}{C}\right)\left(\frac{V}{C}\right)^{k-1}\exp\left(-\frac{V}{C}\right)^{k}.P(V)\,dV \qquad (23)$$

The wind turbine's productivity or some other power generation facility is measured by an element know as capacity factor (C_f). It evaluates the ratio of the turbine's actual production to the rated power the turbine running with entire capability for the same time duration [35]. It can be calculated as;

$$C_f(\%) = \frac{Wind\ \text{energy produced (Wh/year)}}{\text{rated wind energy produced (Wh/year)}}\times 100 \qquad (24)$$

3. Results and Discussion

The Hawksbay coast, near Karachi, is in southern part of Pakistan. The geographic location of wind speed measurement site is 24° 52' 02.025''N and 66° 51' 41.983'' E. The wind data considered in this paper is for 25 months from Apr 2009 to Apr 2011 measured every 10 minutes. The average hourly, daily and monthly wind speed have been calculated at 10m, 30m, 60m and 80m heights. Table 1 shows Monthly mean wind speed for all 25 months. It can be observed that monthly average wind speed at 80m height is more than 5m/s. The mean hourly, daily and monthly wind speed values at different heights are shown in Figure 1.

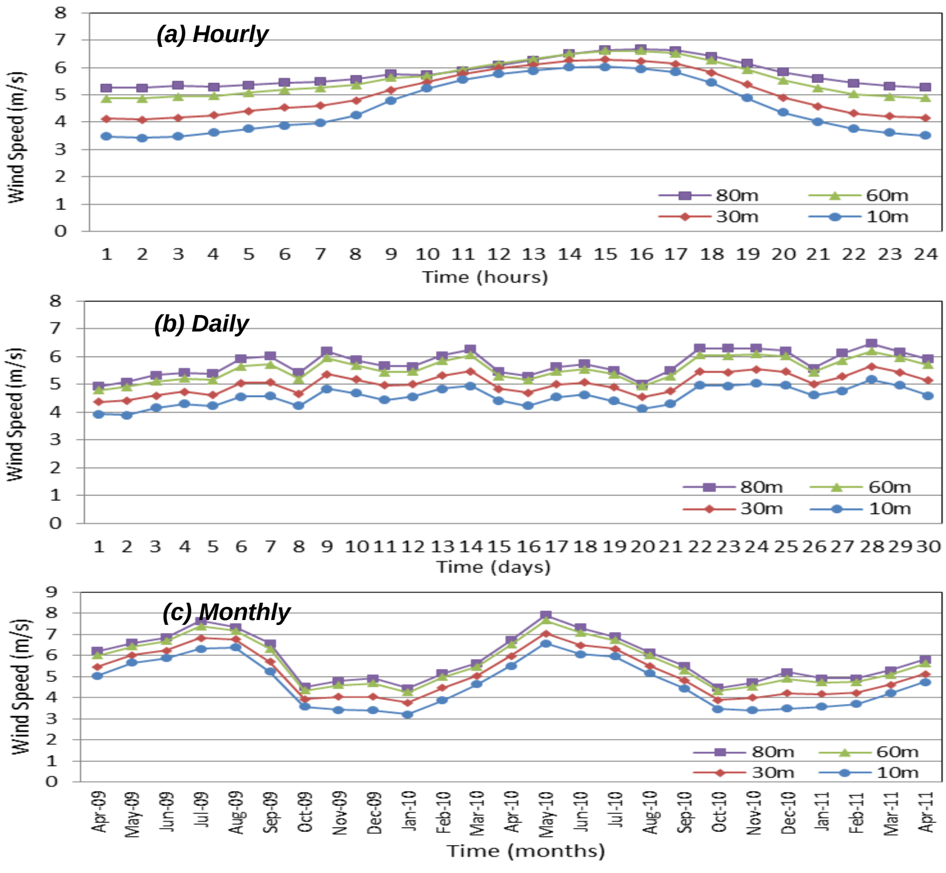

Figure 1. Average Wind Speed at Hawksbay, Karachi

Table 1. Monthly mean wind Speed (m/s) at Hawksbay

Time (Month)	Wind Speed (m/s)			
	80 m	60 m	30 m	10 m
Apr-09	6.215	5.999	5.481	5.041
May-09	6.605	6.437	6.018	5.673
Jun-09	6.852	6.681	6.246	5.883
Jul-09	7.643	7.390	6.825	6.325
Aug-09	7.346	7.172	6.778	6.392
Sep-09	6.574	6.331	5.698	5.231
Oct-09	4.521	4.345	3.940	3.567
Nov-09	4.782	4.595	4.046	3.416
Dec-09	4.923	4.682	4.048	3.405
Jan-10	4.447	4.267	3.768	3.213
Feb-10	5.162	4.974	4.471	3.876
Mar-10	5.641	5.464	5.037	4.644
Apr-10	6.739	6.526	5.976	5.520
May-10	7.928	7.656	7.038	6.577
Jun-10	7.336	7.081	6.491	6.060
Jul-10	6.897	6.736	6.316	5.958
Aug-10	6.149	5.996	5.521	5.157
Sep-10	5.511	5.310	4.837	4.439
Oct-10	4.474	4.319	3.903	3.479
Nov-10	4.724	4.529	4.001	3.414
Dec-10	5.210	4.896	4.204	3.484
Jan-11	4.926	4.721	4.176	3.582
Feb-11	4.924	4.752	4.247	3.704
Mar-11	5.302	5.086	4.620	4.214
Apr-11	5.821	5.625	5.128	4.740

The yearly mean wind power density obtained at Hawksbay is 197.185W/m^2, 179.304W/m^2, 143.222W/m^2 and 117.309W/m^2 at 80m, 60m, 30m and 10m heights respectively. Thus the available annual energy density would be 1727.336kWh/m^2, 1570.699kWh/m^2, 1254.622kWh/m^2 and 1027.624kWh/m^2 of rotor area for the four heights respectively.

Monthly wind power density and average energy density of the rotor area at the four heights is shown in Figure 2 and Figure 3 respectively. It can be noted that the wind power density in summer during the months of April to August is fairly good. The yearly average wind speed, mean wind power density and energy density at different heights are given in Table 2.

The Weibull Scale "*C*" and shape "*k*" and the model prediction performance parameters R^2 and *RMSE* are determined through five methods for four different heights in this study. The Weibull parameters and analysis results are mentioned in Table 3.

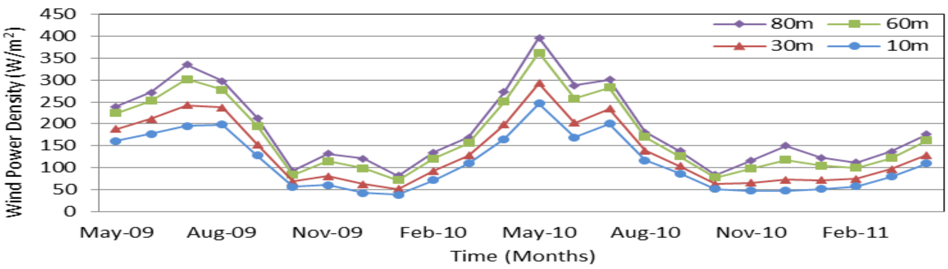

Figure 2. Monthly average wind power density at Hawksbay

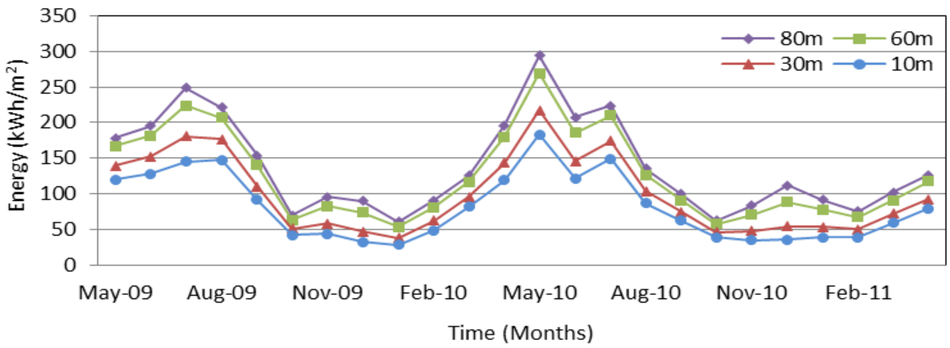

Figure 3. Monthly energy density at Hawksbay

Table 2. Annual mean Wind speed, wind power and energy densities at Hawksbay

Height (m)	$V_{avg.}$ (m/s)	Power density (W/m^2)	Energy (kWh/m^2)
80	5.939	197.185	1727.336
60	5.742	179.304	1570.699
30	5.241	143.222	1254.622
10	4.767	117.309	1027.624

Table 3. Statistical analysis for wind data measured at Hawksbay Karachi

Height	Method	k	C	RMSE	R^2
	MLM	2.5139	6.5913	0.00004263	0.99999994
	MM	2.5321	6.5976	0.00004223	0.99999994
80m	GM	2.2159	5.9833	0.00048150	0.99999199
	MMLM	2.5376	6.5942	0.00004280	0.99999994
	EPFM	2.5004	6.5998	0.00004236	0.99999994
	MLM	2.4939	6.3662	0.00005225	0.99999987
	MM	2.5073	6.3713	0.00005224	0.99999987
60M	GM	2.1870	5.7868	0.00049397	0.99998859
	MMLM	2.5167	6.3679	0.00005328	0.99999987
	EPFM	2.4823	6.3728	0.00005142	0.99999988
	MLM	2.3410	5.8010	0.00007261	0.99999971
	MM	2.3529	5.8039	0.00007352	0.99999970
30M	GM	2.1609	5.1062	0.00055225	0.99998322
	MMLM	2.3647	5.8041	0.00007497	0.99999969
	EPFM	2.3436	5.8046	0.00007251	0.99999971
	MLM	2.0979	5.2784	0.00016402	0.99999789
	MM	2.1065	5.2727	0.00016593	0.99999784
10M	GM	2.0503	4.4907	0.00060251	0.99997149
	MMLM	2.1225	5.2794	0.00016826	0.99999778
	EPFM	2.1239	5.2733	0.00016903	0.99999776

It is observed that the maximum likelihood method, empirical method, modified maximum likelihood method and energy pattern factor method, to determine scale and shape parameters of Weibull distribution, give the good fitting results for wind data collected at Hawksbay site. The graphical method didn't give good fitting results with measured wind speed at four heights in this study.

The Weibull probability distributions obtained from five methods were compared to the measured wind data to find their suitability. Figure 4 depicts the Weibull probability distributions of wind speeds over frequency distribution of wind speeds at four different altitudes.

The comparison between Weibull and Rayleigh distribution of wind speeds over frequency distribution at 80m height, for above mentioned five methods, is shown in Figure 5. Usually at low wind velocities the Weibull distributions fit poorly, however, it is endurable as extremely small power is generated at these wind speeds. It can be observed that the Weibull distribution give better fitting than Rayleigh distribution for wind speed data at the candidate site

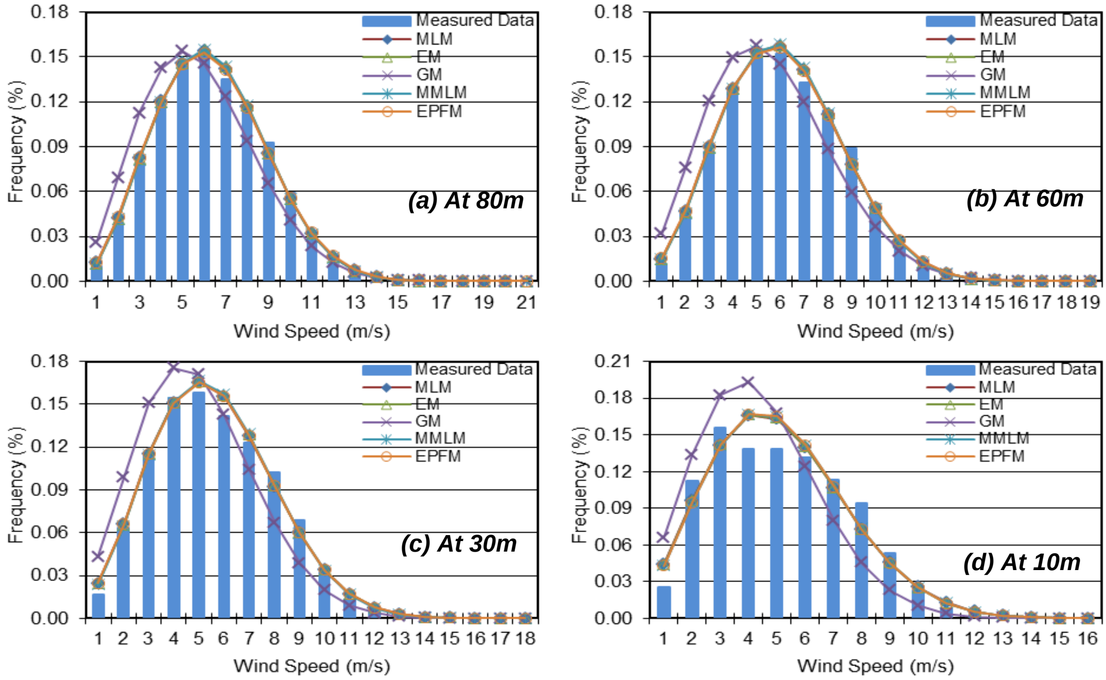

Figure 4. Weibull probability distributions of wind speeds at four heights at Hawksbay

To calculate the yearly energy produce by a wind turbine is one of the necessary steps to assess any wind energy project. The power (or energy) produced at a given site by any particular wind turbine depends not only upon the existence of good wind but also on its hub height, rotor area and the capacity factor (or efficiency).

In this article the annual power generation potential of Nordex N82/1500 and Suzlon S66 wind turbines are calculated as an example. The detail of parameters of Nordex N82/1500 [36] and Suzlon S66 [37] is given in Table 4.

Annual output energy for Hawksbay, Karachi is found to be 5.41GWh with theoretical capacity factor of 0.411 through Nordex N82/1500 at 80m. Annual output energy expected to be generated though Suzlon S66 at the same 80m height is 3.51GWh with theoretical capacity factor of 0.320. The annual output energy expected to be generated through the two wind turbines, used in this study, at height 80m and 60m is given in Table 5.

The study about assessment of wind energy potential at Hawksbay shows that it is suitable site for wind power production projects, like; small stand-alone systems and/or large off-grid or gird connected wind farms in Sindh Pakistan. It is worth mentioning here that a detailed economic evaluation must be done before installing a large wind energy project. Study shows that there is strong wind especially in summer at Hawksbay, when electricity demand amplified due to cooling loads. Thus, it could be beneficial to install wind energy projects to meet the consumer's requirements.

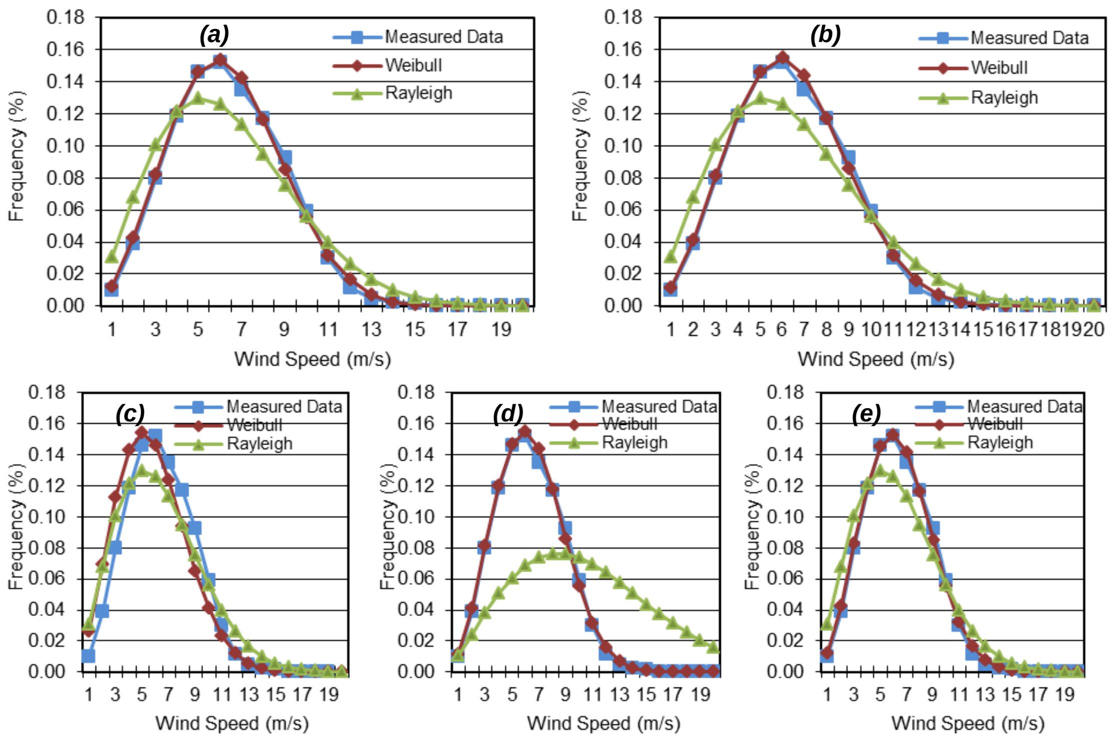

Figure 5. Comparison of Weibull & Rayleigh distribution with measured wind data at 80m height using (a) MLM; (b) EM; (c) GM; (d) MMLM; and (e) EPFM

Table 4. Main characteristics of wind turbines

Turbine model	**Nordex N82/1500 [36]**	**Suzlon S66 [37]**
Rated power (kW)	1500	1250
Rotor diameter (m)	82	66
Hub height (m)	80	54,63,72
Cut-in wind speed (m/s)	3.5	3
Rated wind speed (m/s)	12	14
Cut-out wind speed (m/s)	25	22

Table 5. Estimated annual energy generated through wind turbines and cost/kWh at Hawksbay, Karachi

Turbine model	**Nordex N82/1500**		**Suzlon S66**	
Height (m)	80m	60m	80m	60m
Power Generated (kW)	617.19	561.23	399.83	363.58
Energy Produced (MWh)	5406.59	4916.37	3502.55	3184.96
Capacity Factor	0.411	0.374	0.320	0.291
Cost/kWh (US$)	0.0345	0.0408	0.0443	0.0525

4. Cost Analysis

The estimation of the costs of kWh of energy produced by the turbines has been done with following assumptions:

(a) The lifetime of turbine '*t*' was assumed to be 20 years.

(b) The interest rate *'r'* and inflation rate *'i'* were taken to be 15 and 12%, respectively.
(c) Operation & maintenance and repair cost *'C_{omr}'* was considered to be 15% of the capital cost
(d) Scrap value *'S'* was taken to be 10% of the turbine price and civil work.
(e) Capital cost or initial investment *'I'* includes the turbine price plus its 30% for the civil work and other connections.

Following equation, given by Lysen [38] and referred in the literature to calculate the present value of costs (PVC) of electricity produced per year [39-42]:

$$PVC = I + C_{omr}\left[\frac{1+i}{r-i}\right]\times\left[1-\left(\frac{1+i}{1+r}\right)^t\right] - S\left(\frac{1+i}{1+r}\right)^t \quad (25)$$

The turbine cost is considered as US$1.2/watt. Using the above mentioned assumed values in equation (25) and annual output power/energy from turbines, we get the estimated cost per kWh through Nordex N82/1500 is US$0.0345 and through Suzlon S66 is US$ 0.443 at 80m height. The annual estimated cost per kWh from both wind turbines is given in table 5.

5. Conclusions

Pakistan, presently facing an acute shortage of energy, urgently needs new sources of affordable energy that could alleviate the misery of the energy starved masses. The country is blessed with enormous renewable energy potential but has not been harnessed so far. Wind energy is one of the most suitable and attractive option at present due to sustainability, having low environmental damage and reasonable costs. The data recorded at Hawksbay site shows that the yearly average wind speed is nearly 6m/s at 80m and 60m heights. The estimated energy generated by Nordex N82/1500 wind turbine is 5.41GWh with at 80m height and 4.92GWh at 60m height. The estimated cost per kWh through Nordex N82/1500 is US$0.0345 and through Suzlon S66 is US$ 0.443 at 80m height. The wind energy potential of the considered site has been studied by calculating Weibull scale and shape parameters using five methods. It is observed that only graphical method didn't give good fitting results, whereas other four methods gave better fitting to the measured wind speed data. Study about the assessment of potential of wind resource at Hawksbay indicates its aptness for electricity generation projects. The candidate site is said to be appropriate for small stand-alone as well as large wind power projects. It is also important to mention here that by developing and utilizing wind power would reduce oil import pressure, preserve the environment and evolve the socio-economic conditions of the people of Pakistan.

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