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Estimation of Wind Power Potential of Six Sites in Eastern Cape Province of South Africa

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Authors' contributions

All authors worked as a team to come up with this piece of work. Author CS did the numerical simulation and wrote the paper. Author KM worked with the first author in carrying out the numerical. Author GM supervised the execution numerical simulation and taught the first and third authors to use MATLAB. All authors read and approved the final manuscript.

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ABSTRACT

Aims: To use the five year wind speed measurements to assess the wind power potential of six sites of part of the Eastern Cape Province.
Study Design: The potential for generating electricity from wind was assessed for six sites of the western part of the Eastern Cape Province (Bisho, Fort Beaufort, Graaff – Reinet, Grahamstown, Port Elizabeth and Queenstown)
Place and Duration of Study: The study was carried out at University of Fort Hare, South Africa between June and December 2014.
Methodology: The five-year-long, hourly average wind speed series between January 2009 and December 2013 for the six Eastern Cape weather stations were obtained from South African Weather Services (SAWS). The data was statistically analysed using the Weibull distribution function in MATLAB.
Results: The dimensionless Weibull shape parameter, k, varied from 1.7 to 2.2, while the scale

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parameter, c, varied between 3.5 and 6.3 connected power generation while an average of 3 ms^{-1} to 4 ms^{-1}. The most probable wind speed, v_{mp}, expected in the province ranged from 2.1 to 4.1 connected power generation while an average of 3 ms^{-1} to 4 ms^{-1}. The wind power densities ranged from 34.7 to 207.8 Wm^{-2}. The annual Weibull probability density frequency curves vary from site to site, in both its shape and maximum value and are all skewed towards lower wind velocities except for Port Elizabeth

Conclusion: Basing on the American Wind Energy Association (AWEA) classification, Fort Beaufort, Graaff– Reinet and Queenstown correspond to wind power class 1 while Bisho and Grahamstown correspond to class 2. Consequently they are not suitable for installation of large turbines for grid connection. Nevertheless, they are suitable for stand-alone systems. Port Elizabeth corresponds to class 4 and hence is suitable for grid connected applications. It is thus recommended to install large turbines for grid connected applications in Port Elizabeth and small scale wind turbines for stand-alone applications such as supplying power to individual houses and irrigation in Bisho, Fort Beaufort, Graaff – Reinet, Grahamstown and Queenstown.

Keywords: Wind speed; Weibull distribution; Weibull parameter; wind power density.

1. INTRODUCTION

Worldwide, wind energy is the fastest growing subsector of the renewable energy sector [1]. China, USA, Germany, India, UK, Canada, Spain, Italy, France and Portugal together make the largest contribution (about 86% in 2013) to the share of the global wind-energy installed capacity [2]. Although in the last decade there has been a global growth rate of about 22% in wind energy investments, in South Africa the wind energy share is still very low [1,3]. The country is highly dependent on convectional non-renewable sources such as coal and oil for commercial energy. In remote off grid areas, households depend on biomass in its traditional forms for cooking and heating purposes. This makes the country to be amongst the largest emitters of greenhouse gases in the world [3,4]. Like many other countries, after the ratification of Kyoto Protocol in July 2002, the South African government embarked on numerous projects to abate the effects of climate change. As a result, the 20year Integrated Resource Plan (IRP 2010-2030) approved by the South African parliament in 2010 set a target of about 26.3% renewable energy contribution by the year 2030 [5].

Wind is an unrestricted, inexhaustible and environmentally friendly alternative source of energy which can be used to provide electricity to off grid areas as mini grids for small communities or unconnected systems for discrete loads and homes. Its useful effects on the alleviation of climate change and a chance to reduce reliance on finite sources of energy are unquestionable. Currently the global contribution of wind resource to electricity supply is about 2.5% and is expected to rise to 8 –12% by 2020 [1]. On a local scale in the IRP 2010-2030 of the 26.3% targeted electricity production from renewable sources, 10.3% will be from wind energy [5] hence also making it the greatest contributor in the country. The wind power summit (Wind Power Africa, 2011) held in Cape Town in May 2011 increased the different stakeholders' interest in wind as a resource for electricity generation [6].

Since researchers are coming up with new wind technologies that produce significant electrical energy at lower wind speeds using wind turbines of smaller diameters, the cost of wind technology is expected to go down and be a suitable contender of fossil fuel power plants in the near future [7]. Thus wind uptake is expected to rise even in South Africa. For this to happen there should be a vision of a new way to use the wind, and a conducive political environment to enable it to materialise [8]. As a rule of thumb for uptake of wind technologies, yearly mean wind speeds of 5 ms^{-1} are required for grid-connected power generation while an average of 3 ms^{-1} to 4 ms^{-1} are required for off-grid and mechanical applications such as battery charging and water pumping [9].

The government has committed itself to achieving IRP 2010-2030 targets by signing contracts to invest in 28 projects in wind, solar and small hydro technologies, to be developed in the Eastern Cape, Western Cape, Northern Cape the Free State worth R47 billion [10]. Since wind energy has the greatest share in the renewable energy target, researchers need to avail necessary information to investors about the wind power potential in the country.

It is of paramount importance to assess the wind potential and understand and its characteristics for a particular site because it influences all aspects wind energy exploitation such as systems design, physical performance evaluation and economic viability. To effectively evaluate the wind energy potential of an area, long-term meteorological observations for the location under consideration should be carried out [11]. The longer the period, the more reliable will be the data to predict whether to or not to venture into installing a wind farm or just one wind turbine at a particular site. To this end, meteorologists generally agree that it requires about thirty years of data to establish long-term values of different climatic conditions. Generally about five years are required to get dependable yearly mean wind speed for a particular site [8]. The data is then used to study the wind's statistical characteristics. As a result, many studies have been carried out using a variety of probability density functions (PDFs), which include the Weibull, Rayleigh, gamma, lognormal, and inverse Gaussian to describe wind speed frequency distributions [12]. The Weibull distribution has been recommended for use by many authors since it gives a better fit for wind speed data when compared to other families of distribution [3].

To date there is limited research output on wind resource assessment for the whole Eastern Cape Province which might be one of the factors limiting the development of new wind projects in the province. This study is aimed at using the five year wind speed measurements to assess the wind power potential of six sites of the western part of the Eastern Cape Province. This information is important to different stakeholders if the province is to contribute to harnessing of wind energy to meet the government's IRP 2010-2030 target. It is a prerequisite to decision making process when one wants to invest in wind energy conversion systems.

2. METHODOLOGY

The Weibull distribution function was used to analyse the wind data to ascertain the wind power potential and obtain the wind speed characteristics for the province.

2.1 Wind Speed Data

For the study, five-year-long, hourly average wind speed series between January 2009 and December 2013 for six Eastern Cape weather stations (Bisho, Fort Beaufort, Graaff – Reinet, Grahamstown, Port Elizabeth and Queenstown) compose the database for the statistical analysis. Eastern Cape is one of the nine provinces of South Africa, which borders the Northern Cape, Free State provinces and Lesotho inland as well as the Western Cape and KwaZulu-Natal provinces to the eastern coast. The province is divided into two metropolitan municipalities (Buffalo City Metropolitan Municipality and Nelson Mandela Metropolitan Municipality) and six district municipalities as shown in Fig.1 [13]. Since part of the province is along the eastern coast, it might have substantial places that are suitable sites for setting up wind farms.

The wind speeds data were obtained from South African Weather Services (SAWS). The wind speeds were recorded at an anemometer height of 10 m. The calculations for this study were done for 10 m hub height. Since wind speed increases with height, the wind power output is expected to improve at higher hub heights. The geographical coordinates of these weather stations are shown in Table 1 and the actual location of the sites on the map is shown in Fig. 1.

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2.2 Statistical Estimation of Weibull Parameters

The variation in wind speed at a particular site can be best described using the Weibull distribution function, *f (v, k, c)*, which is given by (1) [14]:

$$f(v;k,c) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \quad \text{for } v > 0 \text{ and } k, c > 0 \qquad (1)$$

The function illustrates the number of hours per month or per year (fraction of time) during which a given wind speed, v (ms^{-1}), can possibly prevail at a particular site. A frequency distribution curve is obtained if the fractional frequency distribution is plotted as a function wind speed. The most frequent wind speed corresponds to the maximum of this curve.

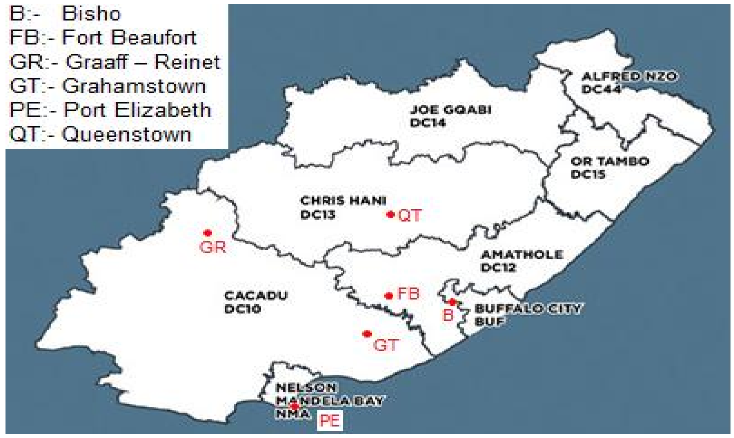

Fig. 1. The Eastern Cape Province
Adapted from [13]

The dimensionless Weibull shape parameter (*k*) shows the wind potential of the location under consideration and indicates how peaked the wind distribution is. A high value of *k*, which will be in the range of 2.5 to 3 indicates that the distribution is more skewed towards higher wind velocities and there is a small variation of hourly mean wind speed about the annual mean [11,15]. The shapes of the frequency and probability distribution curves are related the Weibull distribution and can be explained in terms of the shape factor. If $k = 1$,an exponential distribution curve will be obtained; $k = 2$, a Rayleigh distribution curve will be obtained and $k \geq 3$, a Gaussian or normal-bell distribution will be obtained [14]. Most commercial wind turbines manufacturers give standard performance of wind turbines using this Rayleigh distribution and avoid the Weibull density function because it poorly represents the probabilities of observing zero or very low wind speeds [11]. However when assessing the suitability of a specific site for purposes of installing commercial wind turbines, the Weibull distribution function can be safely used since most commercial wind turbines that are currently on the market are not functional at low wind speeds [11].

The Weibull scale parameter (c,ms^{-1}) shows how 'windy' the location is. It is concerned about the distribution of windy days. The value of *c* increases as number of days with high wind speeds increases. The probability frequency distribution curve against wind speed will shift to the right and the average wind velocity has a higher value [11].

The corresponding cumulative distribution, *F (v, k, c),* can be used to determine the proportion time for which wind speeds (*v*) are greater than a specific wind speed (*u*), *v>u*. It is obtained by finding the integral of the probability density function and it is expressed as [14]:

$$F(v;k,c) = 1 - \exp\left[-\left(\frac{v}{c}\right)^k\right] \tag{2}$$

Various methods have been suggested for the estimation of Weibull parameters k and c. In this study, the mean wind speed - standard deviation is used [1,3];

$$k = \left(\frac{\sigma}{v_m}\right)^{-1.086} \quad 1 \leq k \leq 10 \tag{3}$$

$$c = \frac{v_m k^{2.6674}}{0.184 + 0.816k^{2.73855}} \tag{4}$$

where

σ is the standard deviation of the measured wind speed given by (5):

$$\sigma = \left[\frac{1}{n-1}\sum_{i=1}^{n}(v_i - v_m)^2\right]^{\frac{1}{2}} \tag{5}$$

and v_m is the average of measured wind speeds defined mathematically as:

$$v_m = \frac{1}{n}\sum_{i=1}^{n} v_i \tag{6}$$

Table 1. Geographical coordinates of the weather stations used in the study

Weather stations	Latitude	Longitude	Height(m)
Bisho	-32.8940	27.2860	590
Fort Beaufort	-32.7880	26.6290	455
Graaff - Reinet	-32.1930	24.5430	792
Grahamstown	-33.2900	26.5020	642
Port Elizabeth	-33.9840	25.6100	63
Queenstown	-31.9170	26.8770	1104

with *n* being the number of data set and v_i is the wind speed in time step *i*.

The standard deviation gives the measure of the amount of wind speeds' variation from the mean. A low standard deviation indicates that the wind speeds tend to be very close to the mean velocity and the chances of producing good quality power will be high since there will be no much variation in wind speeds.

2.3 Wind Power Density

Wind power density (P_d) is an all-inclusive guide which gives a better indication of wind power potential for a given location than wind speed [11,16]. It is dependent upon the frequency distribution of the wind speed, the effect of air density on the power available in wind and the cubic power of the wind speed [11]. When assessing the wind resource potential, wind power classes ranging from 1 to 7 according to the American Wind Energy Association (AWEA) are used [9]. Each class represents a range of mean wind power density with corresponding mean wind speed at specific heights above the ground. Wind speeds are usually measured at 10and50 m height. Table 2 shows the 7 classes of wind power density for these two heights and for large scale wind plants, class rating of 4 or higher is preferred [9].

For the Weibull distribution function *(f (v, c, k))*, it can be calculated by the following integration [14]:

$$P_d = \frac{1}{2}\int_0^\infty \rho \bar{v}^3 f(v;k,c)\,dv \tag{7}$$

ρ is the air density (kgm^{-3}) calculated from the ideal gas law (8) and $\bar{V}$ is mean value of the third power of the wind speed.

$$\rho = \frac{p}{RT} \tag{8}$$

R is the specific gas constant (Jkg^{-1}K^{-1}). For dry air it is equivalent to 287 Jkg^{-1}K^{-1}. *T* is the average thermodynamic temperature (K), and *p* is the average pressure (Pa).

Replacing (1) into (7) gives [3]:

$$P_d = \frac{1}{2}\rho c^3 \Gamma\left(1+\frac{3}{k}\right) \tag{9}$$

Γ is the gamma function given by(10).

$$\Gamma(x) = \int_0^\infty t^{x-1} e^{-t}\,dt \tag{10}$$

2.4 Most Probable Wind Speed

The most probable wind speed, (v_{mp}), corresponds to the peak of the probability density function and represents the most likely wind speed to be experienced at a given site [3,17,18]. It is mathematically expressed by (11)

$$v_{mp} = c\left(1-\frac{1}{k}\right)^{\frac{1}{k}} \tag{11}$$

High wind speeds are a requisite for the success of wind power generation but the quality of the power and energy delivery of a wind farm is determined to a large extent by the length of time during which the output remains constant [15]. Therefore more and better quality power is produced if the most probable wind speed is high.

2.5 Optimal Wind Speed

The wind speed that produces the maximum amount of wind energy using a turbine, optimal wind speed (v_{op}), is calculated using (12) [3,17].

$$v_{op} = c\left(1+\frac{2}{k}\right)^{\frac{1}{k}} \tag{12}$$

The importance of v_{op} and v_{mp} is that once they have been obtained, the wind velocities can be linked to the wind turbine operational speed range using equation (13) [18]:

$$\begin{aligned} & v_{op} \le v_{cut-off} \le (2 \text{ to } 4) v_{op} \\ & (1.5 \text{ to } 3) v_{mp} \le v_{rated} \le v_{cut-off} \\ & 0.3 v_{mp} < v_{cut-in} \le 0.8 v_{mp} \end{aligned} \quad (13)$$

where $v_{cut\text{-}off}$ is the fold up velocity in which the wind turbine will shut down, v_{rated} is the velocity at which the system will be operating at its full capacity and $v_{cut\text{-}in}$ is the velocity at which the turbine when the turbine starts to revolve and produce power.

3. RESULTS AND ANALYSIS

3.1 Eastern Cape Province Weibull Parameters

The Weibull parameters for the five year period being considered are presented in Table 3. The values for the Weibull shape parameter, k, ranged from 1.7 to 2.2. These values of are low indicating that there is greater variability of the hourly mean of the wind speed about the yearly mean wind speed. The calculated values of scale parameter, c, varied from 3.5 ms^{-1} for Fort Beaufort to 6.32 ms^{-1} for Port Elizabeth. Table 3 also summarises the calculated values of standard deviation, σ, which ranged from 1.6 to 3.2 for Graaff-Reinet and Port Elizabeth respectively. The interaction of these c and k values resulted in different shapes of the Weibull frequency distribution curves for the specific locations. The optimal wind speed, v_{op}, ranged from 4.94 ms^{-1} for Graaff-Reinet to 9.52 ms^{-1} for Port Elizabeth.

3.2 Eastern Cape Province Wind Speed Characteristics

The mean hourly variations in wind speed are plotted in Fig. 2.

The graph shows that the wind speeds start to increase from almost constant low speed at around 06: 00 to peak between 14:00 and 17:00 hours and then start to decline for all the studied locations.

Table 2. Classes of wind power density

	10 m		50 m	
Wind power class	**Wind power density (Wm^2)**	**Speed (ms^{-1})**	**Wind power density (Wm^{-2})**	**Speed (ms^{-1})**
1	<100	<4.4	<200	<5.6
2	100 - 150	4.4 - 5.1	200 - 300	5.6 - 6.4
3	150 - 200	5.1 - 5.6	300 - 400	6.4 - 7.0
4	200 - 250	5.6 - 6.0	400 - 500	7.0 - 7.5
5	250 - 300	6.0 - 6.4	500 - 600	7.5 - 8.0
6	300 - 400	6.4 - 7.0	600 - 800	8.0 - 8.8
7	>400	>7.0	>800	>8.8

Source [9]

Table 3. The wind speed characteristics and Weibull parameters for Eastern Cape Province for the period under consideration

Parameter	Location					
	Bisho	**Fort Beaufort**	**Graaff-Reinet**	**Grahamstown**	**Port Elizabeth**	**Queenstown**
v_m (ms^{-1})	4.8	3.1	3.2	4.5	5.6	3.6
σ	2.4	1.9	1.6	2.1	3.2	2.0
k	2.1	1.7	2.1	2.2	1.8	1.9
c (ms^{-1})	5.4	3.5	3.6	5.1	6.3	4.0
P_d (Wm^{-2})	130.8	34.7	36.7	105.2	207.8	53.3
v_{op} (ms^{-1})	7.4	5.4	4.9	6.7	9.5	5.9
v_{mp} (ms^{-1})	4.0	2.1	2.6	3.9	4.1	2.7

The daily mean wind speeds for the province are shown in Fig. 3. For the greater part of the studied period Port Elizabeth has the highest daily mean wind speed with the peak of 9.9 ms^{-1} being attained on the 14th of September. Queenstown has lowest daily mean wind speeds for the greater part of the period. These differences could be attributed to the proximity of the places from the sea where the effect of breezes plays an important role in increasing the wind speeds. For all the stations studied, the daily mean wind speeds are generally higher during the second half of the year than the first half.

3.3 Weibull Frequency Distributions

Fig. 4 shows the annual Weibull probability density frequency for part of Eastern Cape Province. The curves vary from site to site, in both its shape and maximum value. They are all skewed towards lower wind velocities except for Port Elizabeth.

The most probable wind speed predicted for Bisho, Fort Beaufort, Graaff–Reinet, Grahamstown, Port Elizabeth and Queenstown are about 4.0, 2.1, 2.6, 3.9, 4.1 and 2.7 ms^{-1} respectively. Furthermore, Port Elizabeth has the lowest v_{mp} probability occurrence of 0.13 and has the highest spread of wind speeds toward high wind speed while Fort Beaufort has the lowest spread among these sites.

For the wind turbine installations to be cost effective, the turbines should produce power for at least 50% of their time [19]. Thus the wind speeds for a given area must be high enough to allow the turbines to be operational for 50% of their time for the area to be suitable. The cumulative frequencies of wind speed for the six sites are shown in Fig. 5. The probability that the wind speeds are more than 5 ms^{-1}, which is the minimum necessary in order to generate electricity for grid-connection [16], for Bisho, Fort Beaufort, Graaff – Reinet, Grahamstown, Port Elizabeth and Queenstown are 0.43, 0.14, 0.13, 0.38, 0.52 and 0.22 respectively.

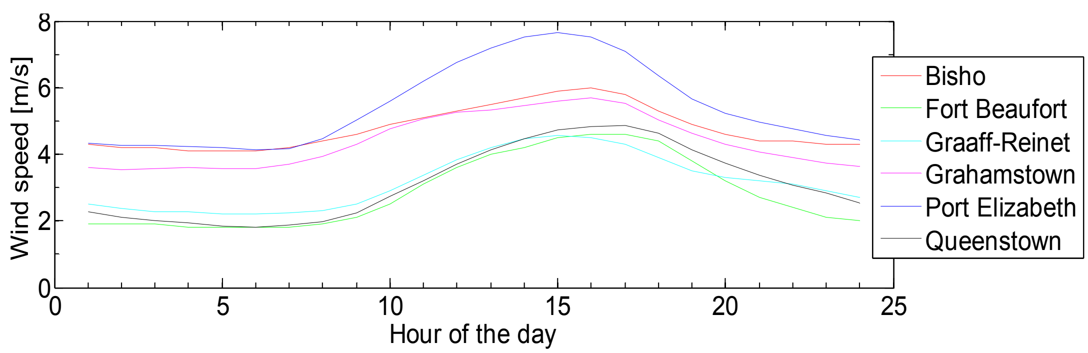

Fig. 2. Diurnal wind speed variation for the six sites between 2009 and 2013

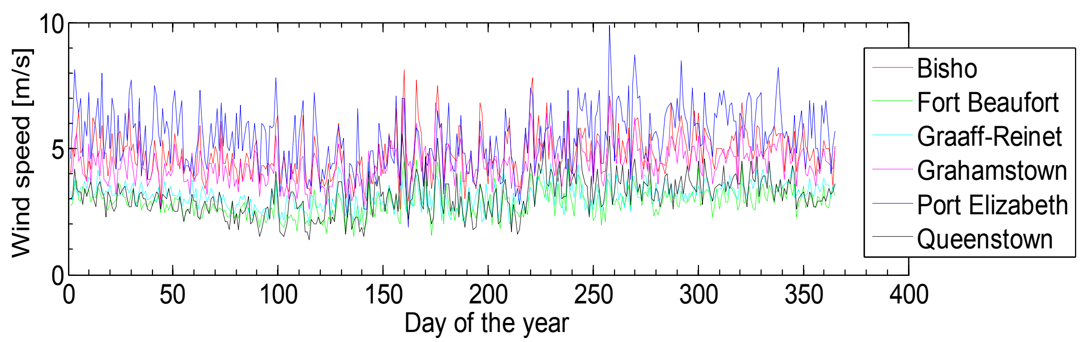

Fig. 3. Daily mean wind speeds between 2009 and 2013 for the six sites

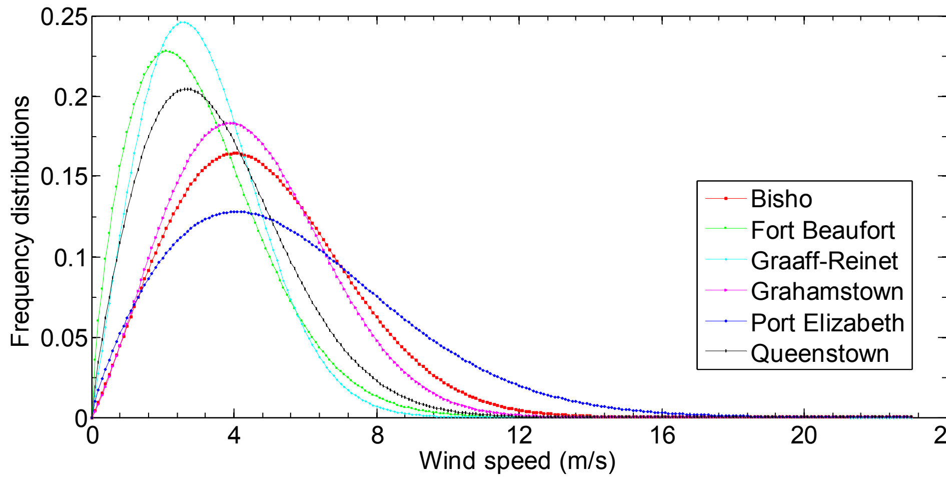

Fig. 4. The annual Weibull probability density frequency for part of the Eastern Cape Province for the period under consideration

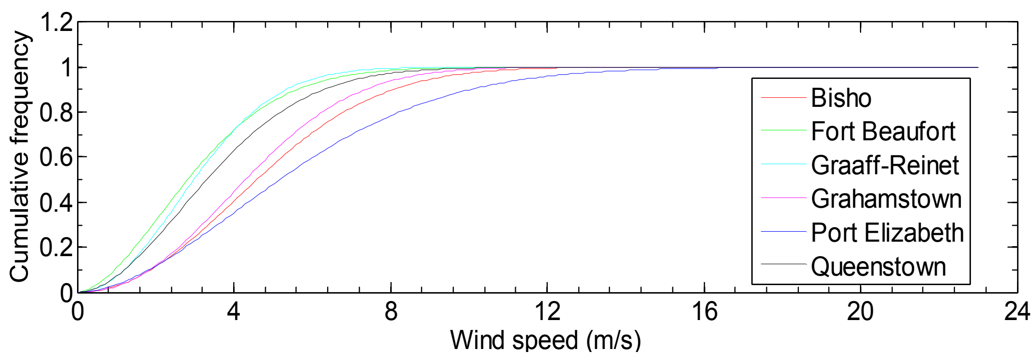

Fig. 5. The annual Weibull cumulative frequency for part of the Eastern Cape Province for the period under consideration

The probability that the wind speeds are greater than 3 ms^{-1}, which is the minimum sufficient for off-grid energy services such as charging batteries and water pumping [16], for Bisho, Fort Beaufort, Graaff – Reinet, Grahamstown, Port Elizabeth and Queenstown are 0.76, 0.46, 0.50, 0.74, 0.77, 0.57 respectively. Hence, from these results, all these sites except for Port Elizabeth are not suitable for large scale grid-connected wind turbines with cut-in speeds of more $v \geq 5$ ms^{-1}.

3.4 Wind Power Density

The wind power densities for the weather stations ranged from 34.7 Wm^{-2} for Fort Beaufort to 207.8 Wm^{-2} for Port Elizabeth. Basing on the AWEA classification given in Table 2, Fort Beaufort, Graaff – Reinet and Queenstown corresponds to wind power class 1 while Bisho and Grahamstown correspond to class 2. Consequently, these locations are not suitable for installation of large turbines for grid connection. Nevertheless, they are suitable for stand-alone systems. Port Elizabeth corresponding to wind power class 4 is suitable for grid connected systems.

4. CONCLUSION

The influence of proximity to the sea is more influential to the available wind resource than the altitude. For example, Port Elizabeth, which is at much lower altitude than the other sites, has the highest available wind resource because of its proximity to the Indian Ocean. For Port Elizabeth that has been studied in the past, the findings of this study are similar to previous findings that are in literature [3]The results for all sites are close to the wind resource map of South Africa [20].The most vital conclusions of the study are summarised below:

1. The low values of the Weibull shape parameter, k, indicate that there is greater variability of the hourly mean of the wind speed about the yearly mean wind speed. This may result in poor quality power being produced by the wind turbines since the quality of the power and energy delivery of a wind farm is determined to a large extent by the length of time during which the output remains constant. This output is largely dependent on wind speed, which is highly variable in this case.
2. Port Elizabeth has a high value of the scale parameter, c, (6.3 ms^{-1}) which is evident by the skewedness of probability frequency distribution curve towards higher wind speeds resulting from a high number of days with high wind speeds. This makes the site ideal for grid connected applications
3. The probability that the wind speeds are more than 5 ms^{-1} is less than 0.50 for all the sites except for Port Elizabeth. Hence basing on the rule of thumb, all these sites except for Port Elizabeth are not suitable for large scale grid-connected wind. However, all the sites have more than 50% chance that the wind speeds are greater than 3 ms^{-1} and hence are suitable for stand-alone electrical and mechanical applications, such as battery charging and water pumping.
4. Basing on the AWEA classification, Fort Beaufort, Graaff – Reinet and Queenstown corresponds to wind power class 1 while Bisho and Grahamstown correspond to class 2.Consequently, they are not suitable for installation of large turbines for grid connection. Nevertheless, they are suitable for stand-alone systems. Port Elizabeth corresponds to class 4 and hence is suitable for installation of grid connected wind turbines.

It is thus recommended to install large turbines for grid connected applications in Port Elizabeth and small scale wind turbines for stand-alone applications including supplying power to individual houses, irrigated areas and small communities in the areas surrounding Fort Beaufort, Graaff – Reinet, Queenstown, Bisho and Grahamstown.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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