

Wind and wind power characteristics of the eastern and southern coastal and northern inland regions, South Africa

Shafiqur Rehman¹, Narayanan Natarajan^{2,*}, Mohamed A. Mohandes³, Joshua P. Meyer⁴,
Md Mahbub Alam⁵, Luai M. Alhems¹

¹ Center for Engineering Research, Research Institute, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia

² Department of Civil Engineering, Dr Mahalingam College of Engineering and Technology, Pollachi, Tamil Nadu 642003, India

³ Department of Electrical Engineering, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia

⁴ Faculty of Engineering, Built Environment and Information Technology, University of Pretoria, Private Bag X20, Hatfield 0028, South Africa

⁵ Mechanical and Automation Engineering Department, Harbin Institute of Technology, Shenzhen Graduate School, University Town, Xili, Shenzhen, China

* Narayanan Natarajan itsrajan2002@yahoo.co.in
Shafiqur Rehman srehan@kfupm.edu.sa
Mohamed A. Mohandes mohandes@kfupm.edu.sa
Joshua P. Meyer josua.meyer@up.ac.za
Md Mahbub Alam alamm28@yahoo.com; alam@hitsz.edu.cn

Abstract

The objective of this work is to understand the fluctuating nature of wind speed characteristics on different time scales and to find the long-term annual trends of wind speed at different locations in South Africa. The hourly average mean wind speed values over a period of 20 years are used to achieve the set objective. Wind speed frequency, directional availability of maximum mean wind speed, total energy, annual energy yield and plant capacity factors are determined for seven locations situated both inland and along the coast of South Africa. The highest mean wind speed (6.01 m/s) is obtained in Port Elizabeth and the lowest mean wind speed (3.86 m/s) is obtained in Bloemfontein. Wind speed increased with increasing latitudes at coastal sites (Cape Town, Durban, East London and Port Elizabeth), while the reverse trend was observed at inland locations (Bloemfontein, Johannesburg and Pretoria). Noticeable annual changes and relative wind speed values are found at coastal locations compared to inland sites. The energy pattern factor, also known as the cube factor, varied between a minimum of 1.489 in Pretoria and a maximum of 1.858 in Cape Town. Higher energy pattern factor (EPF) values correspond to sites with fair to good wind power potential. Finally, Cape Town, East London and Port Elizabeth are found to be good sites for wind power deployments based on the wind speed and power characteristics presented in this study.

Keywords: Wind speed characteristics, Wind power, Plant capacity factor, Wind frequency, Wind turbine

Introduction

Global adverse climatic changes have caused serious and huge losses to property and human lives in the recent past. People from all walks of life have become serious about controlling all means and causes responsible for adverse global climatic changes. In the era of materialistic lifestyles, which are power intensive, more and more power is demanded with passing time and with increasing populations. This global phenomenon is caused by anticlimactic contributions from continents, countries and specific regions and areas within countries. Hence, the contributions to the problem boil down to smaller communities and individuals. The community as a whole has to work on two issues: the conservation of energy resources through the gentle utilisation of energy, and developing and promoting new, clean, self-renewing sources of energy. These sources of energy include wind power, solar (photovoltaic and thermal) energy, geothermal, small and large hydro power plants, as well as biomass, biofuels, ocean tidal, ocean thermal, ocean salinity gradients, ocean currents and ocean waves. Of these, wind power has become commercially accepted and technologically mature. Wind turbines are available in small (kilowatt) to large multi-megawatt sizes. The cost of wind energy has become compatible with traditional means of power generation. Furthermore, wind turbine installation is easy and fast, and requires minimal operational attention and maintenance costs after a proper assessment of wind power resources.

The profitable and lasting wind power deployment in any area requires a proper understanding of wind speed and power characteristics in terms of wind speed variability (diurnal, seasonal and annual), vertical, frequency in different bins, and ultimately wind power and plant capacity factor availability and variability. As a result of such successful studies, wind power is used in a large number of countries and is progressing continuously. The cumulative global wind power capacity reached 650.758 GW at the end of 2019, an increase of 10.1% compared to 2018 (591.091 GW). In terms of annual additions, a record increase of 19% was observed in 2019 (59.667 GW) compared to 2018 (50.252 GW) Weblink 1 (2020). Among global wind power developers, China took the lead with a global standing at 237.029 GW, while the USA, Germany, India and Spain stood in second, third, fourth and fifth place with total installed capacities of 105.433, 61.357, 37.529 and 25.808 GW, respectively. With respect to South Africa, wind energy deployment is growing in different parts of the country and had achieved a cumulative installed wind power capacity of 2.2 GW by the end of 2019 Weblink 2 (2020). It is forecast that wind power will contribute around 17.8% of annual energy generation in South Africa by 2030.

Wind speed distribution is very well represented with two-parameter Weibull distribution, as seen from the literature (Hulio et al. 2019; 2017; Shoaib et al. 2017; Baseer et al., 2017a, b; Bagiorgas et al. 2016; Bassyouni et al. 2015; Bagiorgas et al. 2012; Rehman et al. 2012; Fagbenle et al. 2011). Wind power potential assessment studies have been conducted in different parts of the globe (Shoaib et al. 2019; Himri et al. 2016; 2008; 2012; Rehman 2005; 2004; 2003). Such studies reflect the importance of such investigations before real-time wind farm deployments. Furthermore, an accurate long-term understanding of wind speed and power characteristics is the backbone of successful wind power development (Baseer et al. 2015; Rehman and Al-Abbadi 2010; Rehman et al. 2009; Al-Abbadi and Rehman, 2009; Rehman and Al-Abbadi 2008; 2007; 2005; Rehman et

al. 2018). Rehman et al. (2020a) studied wind power potential, considering topographical features for various locations in Tamil Nadu, India. Later in the year, Rehman et al. (2020b) utilised 38 years of hourly mean wind speed data from seven locations along the coast of Tamil Nadu for providing the accurate wind power assessment and understanding the longitudinal behavior of its characteristics. Natarajan et al. (2021) analysed the wind energy potential of 25 cities located in the state of Tamil Nadu, India, using trend analysis. Assowe Dabar et al. (2019) assessed the wind power resources at eight sites in the Republic of Djibouti using three years of measured wind speed data, and found three locations (GaliMaba, Ghoubbet and BadaWein) to be potential candidates for wind farm deployment, with annual mean wind speeds greater than 6.0 m/s. Three wind farms with a total installed capacity of 275 MW at the above sites could produce 1073 GWh of electricity annually at an energy cost of 7.03 to 9.67 US\$ cents/kWh. Himri et al. (2016) studied wind characteristics like mean wind speed, energy flux, prevalent wind direction, frequency distribution and the Weibull distribution for wind power resource assessments for the Adrar region in Algeria. The study revealed that a wind farm at Adrar was feasible and could produce 3146 MWh of energy annually, with a 36% plant capacity factor at an energy cost of 3.25 US\$ cents/kWh. Rafique et al. (2018) and Rehman et al. (2011) reported the techno-economic feasibility of developing 100 and 20 MW of installed capacity of wind farms under different climatic conditions. Baseer et al. (2017a, b) used GIS multi-criteria-based potential site selection for wind farm deployment in Saudi Arabia. Rehman (2006) and Rehman (2004) assessed wind power resources for coastal locations, giving another indication of the importance of prior knowledge of wind power variability.

Wind resource assessment studies have been performed in South Africa and are reported in the literature. Gough et al. (2019) used high-resolution annual wind speed measurements from six locations in Cape Town to quantify and analyse the city's urban wind energy potential. Pullinger et al. (2019) addressed two key objectives using operational performance data from most of the Round 1 wind farms connected to the grid in South Africa, namely, benchmarking of the wind farm performance and validation of the pre-construction energy yield assessments. Inambao and Cunden (2019) performed off-shore wind resource assessments off the South African coastline. The African continent has large wind power potential, which is underutilised Mas'ud et al. (2017). However, some African countries in the Middle East and North Africa region, as well as South Africa, have adopted wind power in their energy mix. South Africa alone is supplying up to 26,000 GWh of electricity to the national grid annually. Additionally, Cameroon and Nigeria have vast wind potential, but are lagging behind due to a lack of finances and policy.

Wright and Grab (2017) studied the spatio-temporal dynamics of near-surface winds across the Cape regions of South Africa and reported a decrease of -0.002 to -0.06 m/s per year in mean wind speed across all stations over the 20 years. According to Fant et al. (2016a, b), the wind speed parameter is highly fluctuating and intermittently variable on various time scales (hourly, daily, monthly and yearly), and occasionally has a negative impact on the stability of the grid. Hence, a better understanding of this variability can greatly benefit power grid planning. Touafio et al. (2020) conducted a techno-economic analysis of wind power generation in the west of the Central African Republic and reported a cost of energy of 0.081 US\$/kWh. For further reading on the development of renewable energy in general and wind power in African countries and South Africa in particular, researchers are referred

to studies by various authors (Nobela et al. 2019; Sterl et al. 2018; Kazimierczuk 2019; Fant et al., 2016a, b; Moner-Girona et al. 2019; Ferrari et al. 2020).

The study presented a comprehensive wind speed and power characteristics for both inland and coastal locations together over a fairly long period of data from 2000 to 2019. Furthermore, every data set is a unique contribution and adds new and unknown information to the literature. In the current study, the wind speed and wind power characteristics for potential coastal and inland sites of South Africa are analysed for resource assessment. Specifically, long-term annual, monthly and diurnal mean wind speed, wind speed frequency distribution at different heights above 3.0 m/s bin, prevailing wind direction, the directional quantification of maximum mean wind speed and total energy contributions, annual wind energy yield and the plant capacity factor for seven types of wind turbines of 2.0 MW rated powers each are analysed. Finally, an annual mean wind speed trend analysis is performed to understand the availability of wind in future.

Site information and data description

Seven sites in South Africa have been considered for this study: Bloemfontein, Cape Town, Durban, East London, Johannesburg, Port Elizabeth and Pretoria. The latitude, longitude and elevation of these sites are provided in Table 1 and the geographical locations are shown in Fig. 1. Column 3 in Table 1 provides the abbreviations used for the chosen locations throughout the text. Of the seven locations, four are located in the coastal regions (Durban, East London and Port Elizabeth on the east coast and Cape Town on the extreme southern end of the country). Pretoria and Johannesburg are located in the northern inland area, while Bloemfontein is located in central South Africa. All three sites on the eastern coast are located at smaller altitudes varying from 20 to 60 m above mean sea level, while other locations are at higher altitudes of around 1500 m above mean sea level. In this study, hourly average values of mean wind speed over a period of 20 years from 2000 to 2019 are considered (Bosilovich et al. 2016). The data was checked for completeness and erroneous values before a statistical analysis was conducted for all the sites.

Table 1. Site-specific geographical information

S. no.	Location	Abbreviation	Latitude (°S)	Longitude (°W)	Altitude (m)
1	Bloemfontein	BLF	29.0852	26.1596	1395.0
2	Cape Town	CPT	33.9249	18.4241	1590.0
3	Durban	DRB	29.8587	31.0218	21.0
4	East London	ELD	33.0292	27.8546	48.0
5	Johannesburg	JHB	26.2041	28.0473	1753.0
6	Port Elizabeth	PEZ	33.9608	25.6022	60.0
7	Pretoria	PRT	25.7479	28.2293	1339.0



Fig. 1. Location map of the selected sites

Materials and methods

Proper knowledge of wind speed frequency distribution is important in evaluating the potential of a particular location. There are many distribution functions that are prevalent for the description of wind speed frequency, such as Weibull, Rayleigh and lognormal, but the commonly used function is the Weibull distribution (Shoaib et al. 2017; Bagiorgas et al. 2016; Bassyouni et al. 2015; Bagiorgas et al. 2012; Rehman et al. 2012). This function is given by the probability density function $f(v)$ (Akpinar and Akpinar 2005) as:

$$f(v) = \left(\frac{k}{c}\right) \left(\frac{v}{c}\right)^{k-1} \text{Exp}\left[-\left(\frac{v}{c}\right)^k\right] \quad (1)$$

where v , c and k refer to wind speed, scale and shape parameter, respectively. The mean wind speed is used to measure the potential of the wind energy production and is termed V_{mean} . The mean and variance of the wind speed are expressed as follows:

$$V_{\text{mean}} = \frac{1}{N} \sum_{i=1}^N V_i \quad (2)$$

$$\sigma^2 = \frac{1}{N-1} \sum_{i=1}^N (V_i - V_{\text{avg}})^2 \quad (3)$$

The wind power is calculated using the following equation (Penchah et al. 2017):

$$P_w = \frac{1}{2} \rho A_T V^3 \quad (4)$$

where P_w is the wind power, V is the speed, ρ is the air density and A_T is the swept area of the wind turbine rotor. The wind power density is calculated using the Weibull probability density function as follows (Ucar and Balo 2009):

$$\text{WPD} = \frac{P}{A_T} = \frac{1}{2} \rho c^3 \Gamma\left(\frac{k+3}{k}\right) \quad (5)$$

where P , ρ , A , V and Γ are power in Watts, average density of air in kg/m^3 (1.23 kg/m^3 for atmospheric pressure at sea level at 15°C), area perpendicular to the wind speed vector in m^2 , wind speed in m/s and gamma function, respectively. By knowing the wind power density, the wind energy density can be calculated using the following expression Fant et al. (2016a, b):

$$\frac{E}{A} = \frac{P}{A} T = \frac{1}{2} \rho c^3 \Gamma\left(\frac{k+3}{k}\right) \quad (6)$$

Results and discussion

The long-term hourly mean wind speed, direction and other meteorological parameters are used to obtain the site-dependent statistics. The results are summarised in Table 2. Among the selected sites, the highest mean wind speed (6.01 m/s) is noticed at Port Elizabeth and the lowest mean wind speed (3.86 m/s) is noticed at Bloemfontein. An increasing trend of wind speed, from 4.14 to 6.01 m/s , with increasing latitudes (corresponding to Durban to Port Elizabeth) is seen in Table 1. Another observation is the high wind speeds that are observed at coastal locations relative to inland sites (Bloemfontein, Johannesburg and Pretoria). At inland sites (Bloemfontein, Johannesburg and Pretoria), an increasing trend is observed in mean wind speed values (from 3.86 to 4.21 m/s) with decreasing latitudes, which is just the reverse of the coastal location pattern.

The small values of the Weibull shape parameter (k) indicate very weak wind speed, while higher values above 2.0 indicate even occurrences of high and low wind speeds at the site. In the present scenario, k values are above 2.0 for all the sites. The scale parameter variability is the same as the mean wind speed with a difference in magnitude only. The EPF, also known as the cube factor, is calculated as the ratio of the actual wind power density to that calculated using wind speed at constant air density. The EPF varies between a minimum of 1.489 at Pretoria and a maximum of 1.858 at Cape Town. Higher EPF values correspond to sites having fair to good wind power potential. The long-term mean, minimum and maximum values of ambient temperature, pressure and air density are also included in

Table 2 to get an idea of the climatic conditions at these sites under investigation. At all these sites, the overall mean temperatures are observed around 20.0 °C.

Table 2. Long-term summary of meteorological parameters

Parameters/locations	BLF	CPT	DRB	ELD	JHB	PEZ	PRT
Mean WS (m/s)	3.86	5.574	4.144	5.801	4.147	6.01	4.212
Max WS (m/s)	15.83	25.26	13.69	20.02	14.02	20.88	14.03
Shape (k)	2.299	2.056	2.625	2.338	2.686	2.358	2.721
Scale (c - m/s)	4.358	6.292	4.664	6.547	4.664	6.782	4.735
Energy pattern factor	1.683	1.858	1.524	1.660	1.501	1.649	1.489
Wind power class	1 (Poor)	3 (Fair)	1 (Poor)	3 (Fair)	1 (Poor)	4 (Good)	1 (Poor)
Temperature (°C)							
Mean	21.07	19.67	21.92	20.57	21.56	19.66	21.80
Minimum	00.07	8.62	1.28	9.06	-1.37	7.27	-1.41
Maximum	45.14	28.24	45.38	28.43	44.76	28.84	44.95
Pressure (mb)							
Mean	1008.0	1016.1	998.9	1014.4	985.5	1014.6	983.7
Minimum	990.3	993.3	983.3	992.2	969.8	986.8	969.0
Maximum	1028.3	1038.6	1017.6	1034.0	1003.6	1035.2	1001.7
Air density (kg/m ³)							
Mean	1.175	1.187	1.165	1.183	1.149	1.184	1.146
Minimum	1.074	1.135	1.066	1.133	1.052	1.132	1.049
Maximum	1.282	1.252	1.267	1.246	1.258	1.250	1.255

Mean wind speed trend analysis

The hourly mean wind speed values were used to obtain the annual, monthly and diurnal means at all the sites. The annual mean values (Fig. 2) clearly indicate the magnitudes of the wind speed at coastal and inland locations. The coastal locations are identified with high mean wind speed, while inland locations are identified with relatively lower values. The linear trend lines obtained using best fit regression analysis showed decreasing wind speeds with passing time at most of the locations. However, increasing trends were observed at Bloemfontein (+0.0002 m/s per year, Eq. 7) and Cape Town (0.0031 m/s per year, Eq. 8). In these equations, (7 to 13), x is the year, y is the mean wind speed and R^2 is the coefficient of determination. The highest decreasing rate (-0.0033 m/s per year) of annual mean wind speed was observed at Pretoria.

$$\text{BLF : } y = 0.0002x + 3.8592; R^2 = 5E-05 \quad (7)$$

$$\text{CPT : } y = 0.0031x + 5.5414 R^2 = 0.0163 \quad (8)$$

$$\text{DRB : } y = -0.0047x + 4.1928 R^2 = 0.0796 \quad (9)$$

$$\text{ELD : } y = -0.0027x + 5.8297 R^2 = 0.0057 \quad (10)$$

$$\text{JHB : } y = -0.003x + 4.178 \quad R^2 = 0.0277 \quad (11)$$

$$\text{PEZ : } y = -0.0028x + 6.0409 \quad R^2 = 0.0097 \quad (12)$$

$$\text{PRT : } y = -0.0033x + 4.2468 \quad R^2 = 0.0299 \quad (13)$$

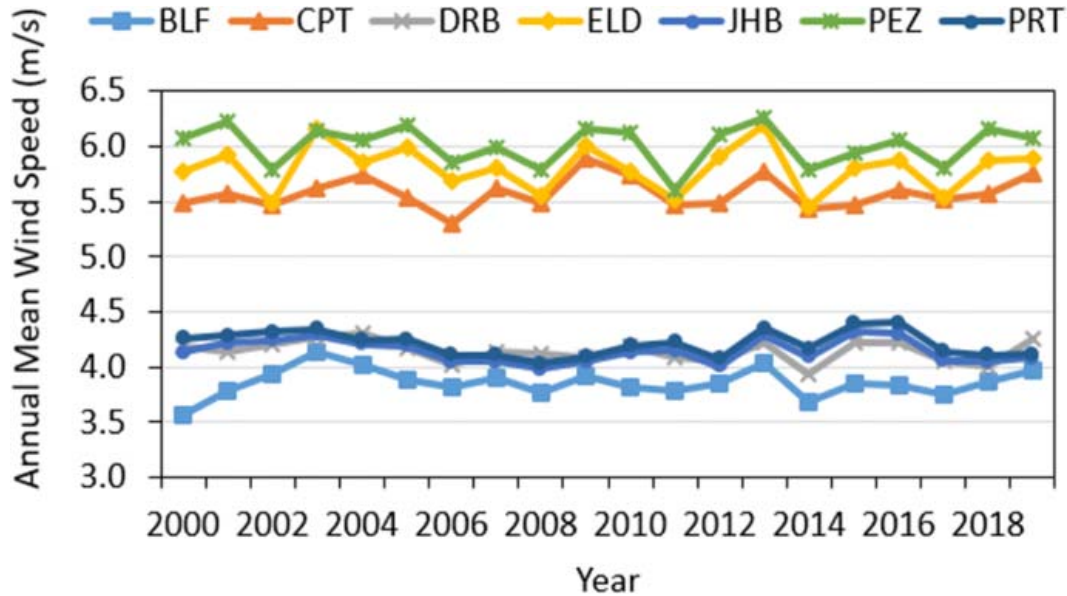


Fig. 2. Long-term annual mean wind speed variation

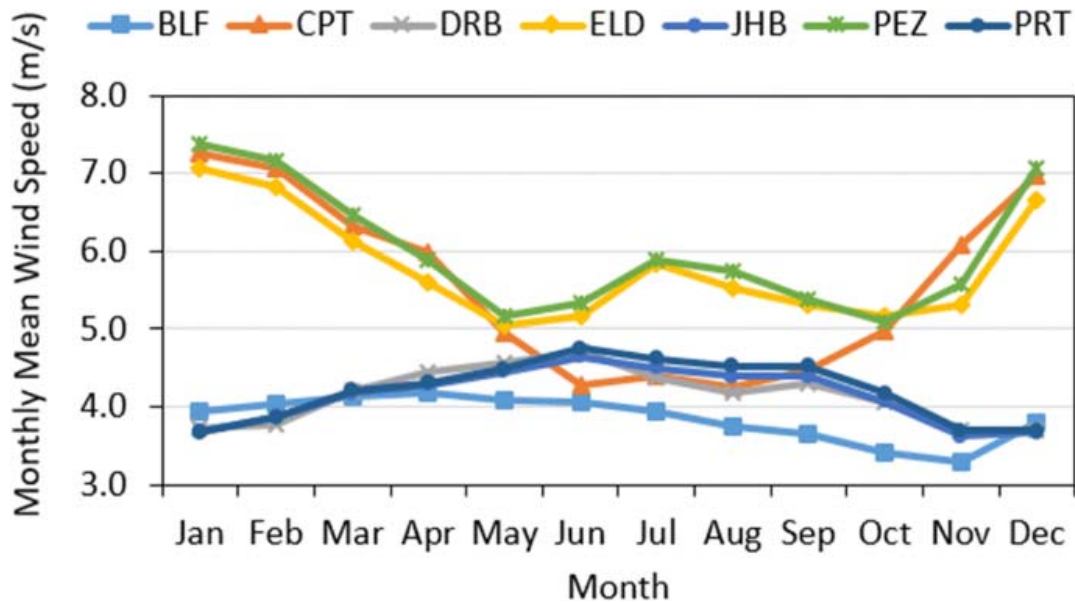


Fig. 3. Long-term monthly mean wind speed variation

As depicted by the monthly trends (averaged over a period of 20 years from 2000 to 2019), higher monthly mean values are observed at coastal locations and lower values are observed at inland sites (Fig. 3). At Cape Town, higher speeds are observed during the summer months of January to May and October to December), and lower speeds in the

winter months (June to September). However, at other coastal sites (East London and Port Elizabeth), wind speeds fall back again in October after reaching a minimal speed in May, regaining this speed until July (Fig. 3). The seasonal trends at other inland locations are seen to be the reverse of that observed at coastal sites. Again, higher magnitudes of wind speed are obtained at coastal sites compared to inland locations.

A knowledge of the diurnal variation of hourly mean wind speed is important to understand the availability of wind power according to the load variability during the day cycle. Here, it is evident that the wind speed varies slightly from 5.5 to 6.0 m/s during a 24-h cycle at coastal sites (Cape Town, East London and Port Elizabeth), which means less fluctuation and stable wind power availability at these sites (Fig. 4). The diurnal pattern at coastal sites shows slightly higher values during the early and late hours of the day. At inland locations (Bloemfontein, Johannesburg and Pretoria), a diurnal change is observed in mean wind speed values (Fig. 4). Higher values above 4.0 m/s are observed from 08:00 to 17:00, which may be advantageous for wind power utilisation during the day at these sites.

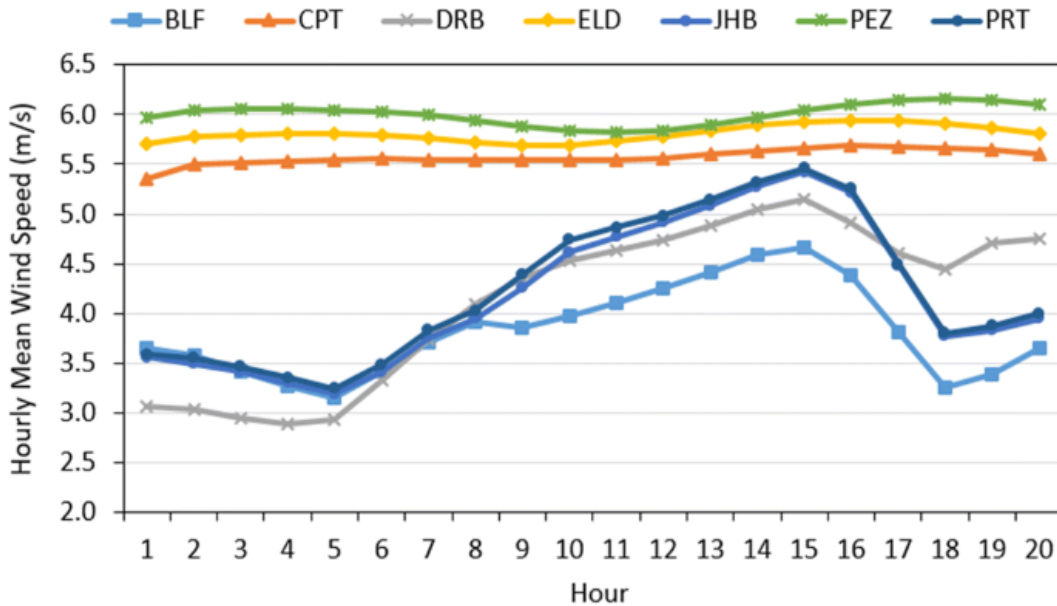


Fig. 4. Long-term diurnal mean wind speed variation

Weibull parameters and mean wind power density analysis

Weibull distribution is an excellent distribution used globally for wind speed representation. In this study, two parameters (shape and scale) of the Weibull distribution are used to describe mean wind speed frequencies at different heights. The resulting shape parameter (k) values are shown in Fig. 5 (annual variation) and Fig. 6 (monthly variation). The highest and lowest k values correspond to Pretoria (an inland location) and Cape Town (a coastal site). For the rest of the sites, these values vary from 2.0 to 3.0. Nonetheless, no definite trend of k values could be established with the passage of time (Fig. 5). However, an increasing trend of k values is observed from January to July, with the values then decreasing towards the end of the year for almost all locations. In this scenario, the highest k values are observed at Pretoria, Johannesburg and Durban, with exceptional peaks

in July and August at East London and Port Elizabeth (Fig. 6). In general, higher k values are observed at inland sites than at the coast. The annual and monthly variations or trends of the Weibull scale parameter (c) are exactly the same as those of the mean wind speeds (Fig. 2 and Fig. 3), except that the magnitudes are relatively greater. Keeping this similarity in mind, and at the same time conserving space, scale parameter values are not shown here.

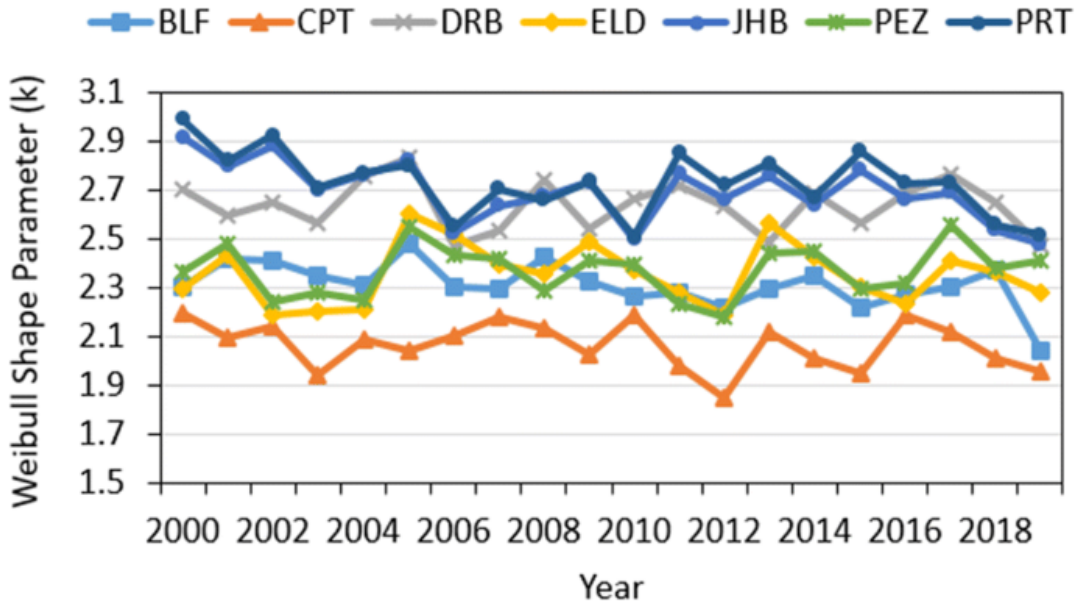


Fig. 5. Annual variation of Weibull shape parameter (k)

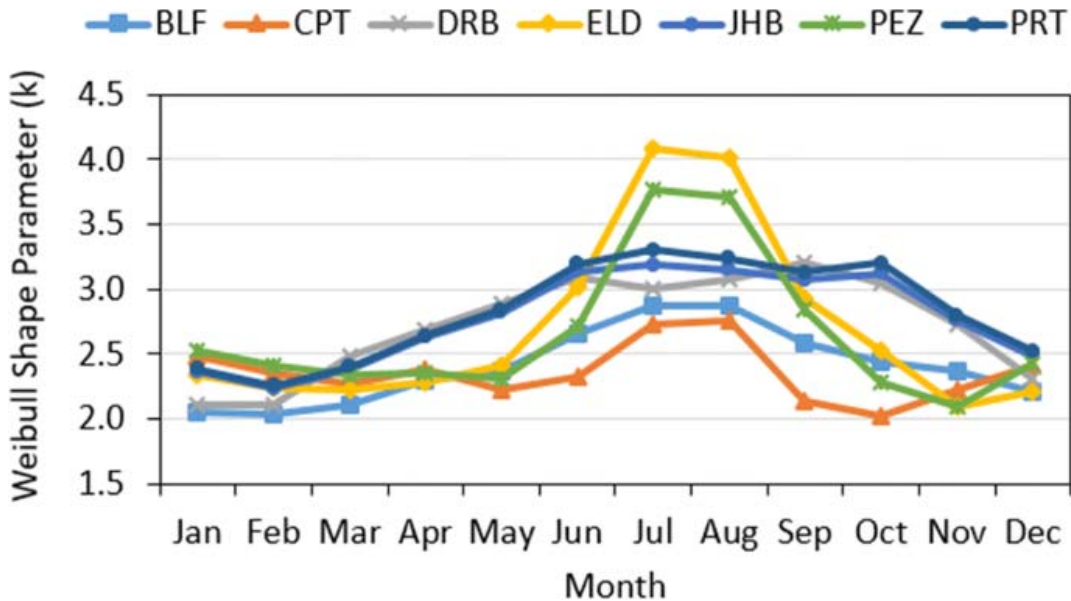


Fig. 6. Monthly variation of Weibull shape parameter (k)

Wind power density values are calculated using the equations described in the “Materials and methods” section at a hub height of 120 m. Since the actual hourly mean wind speeds were available at only 10 m above ground level, the wind speed values were calculated at 30, 50, 70, 90, 110 and 120 m above ground level using wind power law, which is widely

used worldwide. In this vertical extrapolation of wind speed, the wind shear exponent value of 0.14 was used. The study opted for a hub height of 120 m for the chosen wind turbines for energy yield and plant capacity factor estimations. Wind power density values are calculated at 120 m above ground level using the synthesised hourly mean wind speed values at the same height. Similar to annual mean wind speed variation, the wind power density values also show an evident difference in the magnitudes for coastal and inland sites (Fig. 7). At Bloemfontein, Durban, Pretoria and Johannesburg, the wind power density values vary in a narrow range of 150 to 200 W/m², but at Cape Town, East London and Port Elizabeth, these values vary from 450.0 to 700.0 W/m², which is a wide range, during the entire data reporting period.

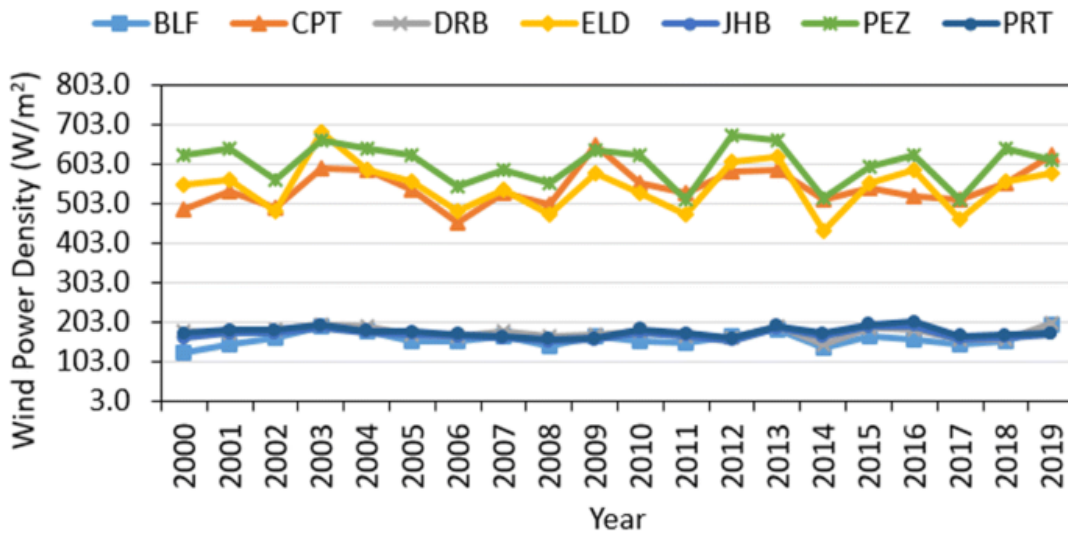


Fig. 7. Annual variation of wind power density at hub height = 120 m

Higher wind power density (WPD) values are observed at coastal sites than at inland locations. It is noticed that, at inland locations, the WPD values vary within a narrow range around 200.0 W/m² and no obvious seasonal trend was visible. However, at coastal sites, higher values are seen in winter and a decreasing trend was observed between January and August, where it touched its minimum (184.0 at Cape Town, 337.7 at East London and 374.4 at Port Elizabeth), and then started increasing again towards the end of the year (Table 3).

Table 3. Monthly mean wind power density (W/m^2) at hub height = 120m

Month	BLF	CPT	DRB	ELD	JHB	PEZ	PRT
Jan	195.6	1036.9	159.7	1003.9	138.6	1082.3	135.9
Feb	213.6	999.5	165.6	939.1	166.7	1020.2	164.0
Mar	217.2	735.2	195.0	681.6	195.8	769.3	198.0
Apr	206.1	596.8	217.7	506.8	192.7	576.7	195.2
May	181.8	354.4	218.9	348.0	203.0	388.3	207.8
Jun	163.5	218.2	230.1	321.5	215.1	374.0	227.8
Jul	142.4	206.6	186.1	399.2	193.4	421.1	204.8
Aug	122.4	184.9	160.8	337.7	180.2	391.7	194.5
Sep	122.9	263.0	173.7	352.4	184.6	374.4	199.9
Oct	106.4	385.9	151.3	359.5	148.3	372.7	158.4
Nov	99.6	655.3	124.6	458.4	115.3	534.3	121.0
Dec	164.1	936.2	143.0	871.0	131.7	966.2	132.6

Wind frequency analysis

Wind frequency distribution provides information about the availability of wind speed in different wind speed bins, and it is important to properly assess the wind power potential at a site. Frequency distributions (as an example) at different heights are shown in Fig. 8 at Bloemfontein, an inland location. It is evident from these figures, that, as the weight increases, the peak shifts towards the left, which means higher wind speed availability at higher heights. To better understand this, wind speed availability above 3.0 m/s (the usual cut-in speed of wind turbines) is summarised in Table 4 at different heights.

Table 4. Summary of wind availability above 3.0 m/s at different heights

Height (m)	BLF	CPT	DRB	ELD	JHB	PEZ	PRT
10	67.4	82.0	73.4	87.1	78.0	87.8	76.6
30	78.8	87.3	83.5	90.7	86.9	91.2	87.7
50	82.9	89.1	87.0	92.0	89.5	92.5	90.0
70	85.1	90.1	89.0	92.8	90.9	93.2	91.2
90	86.5	90.8	90.3	93.3	91.7	93.7	92.0
110	87.5	91.4	91.1	93.7	92.3	94.1	92.5
120	88.0	91.6	91.5	93.9	92.6	94.2	92.7

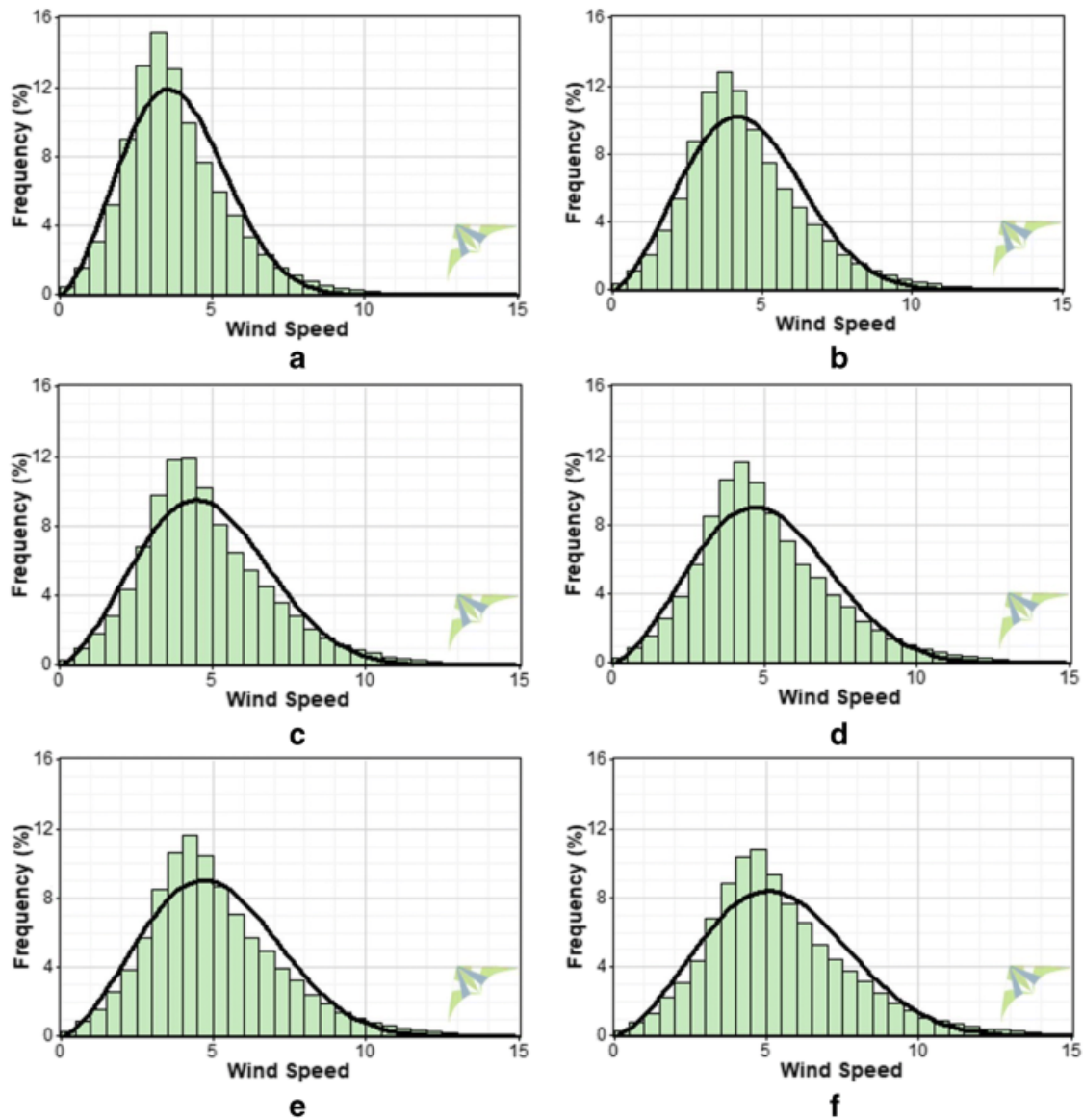


Fig. 8. Effect of height on wind frequency distribution at the Bloemfontein site. **a** Wind frequency at 10 m AGL. **b** Wind frequency at 30 m AGL. **c** Wind frequency at 50 m AGL. **d** Wind frequency at 70 m AGL. **e** Wind frequency at 90 m AGL. **f** Wind frequency at 120 m AGL

It is evident that the frequency of wind speed above 3.0 m/s increases with height, and there is a significant increase at 30 m compared to that at 10 m. At Bloemfontein, the frequency at 10 m is 67.4%, while at 30 m it increased to 78.8%, which is a large jump. However, with a further increase in height, the rate of change of frequency slows down, as can be understood from the frequency values at 50 m, 70 m, etc. Between heights of 70 and 120 m, the rate of increase of wind frequency availability above 3.0 m/s becomes negligible (0.5 to 1.0% only). It is also clear that higher frequencies are observed at coastal sites (Cape Town, East London and Port Elizabeth). It is worth mentioning that the change in frequency with height at coastal locations is found to be under 1.0% for each height step above 70 m.

This simply means that increasing hub height further may not be useful from a wind power generation point of view.

Directional variation of wind speed and energy

Wind rose diagrams are very helpful in defining the prevailing wind direction, the directional quantification of total energy and the direction of maximum wind speed intensity. Wind speed, frequency and total energy variation with wind direction are only shown here for Bloemfontein, and the others are explained. The highest mean wind speed is observed to be coming from the west at Bloemfontein, as shown in Fig. 9a. On the other hand, the wind mostly blows from west-north-west, north and north-west, as shown in Fig. 9b. However, the maximum total energy is expected to be obtained from a west-north-west direction and is distributed up to north-east. At Cape Town, the highest wind speed blows from deep south-east, and the prevalent wind comes from the west and west-north-west about 46% of the time. Higher wind speed values are observed to be distributed all the way from the south to the north-east at Cape Town. Around 51% of the total energy is observed to be obtained from westerly and west-north-west directions at Cape Town. Around 60% of the time, the wind blows from the north-west and north at Durban and a similar volume of total energy is expected from almost the same direction.

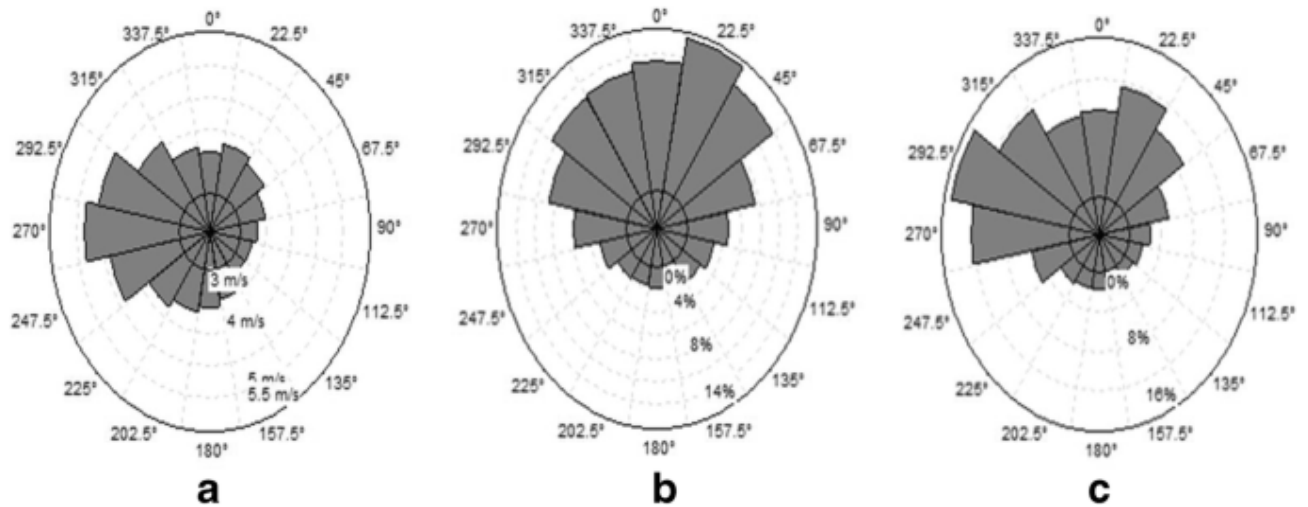


Fig. 9. Directional variation of mean WS, frequency and energy at Bloemfontein. **a** Mean wind speed directional variation. **b** Wind speed frequency directional variation. **c** Total energy directional variation

Most of the wind (60%) and total energy contributions come from a north-westerly direction at the East London site. However, the maximum mean wind speed comes mostly from the south-westerly and north-westerly directions. Around 60% of the wind blows from the north-north-east and north-north-west, and more than 75% of the total energy share is expected to come from northerly and north-westerly directions at Johannesburg. The maximum mean wind speed is observed from the north-west and distributed in all directions. At the Port Elizabeth site, around 80% of the time, the wind blows from the

north and north-west, and around 72% of the total energy comes from the northerly to westerly directions. Mostly, a mean wind speed above 6.0 m/s is observed to flow from any direction (north, east, south, or west), which means that it is distributed between 0 and 360°. At the Pretoria site, the wind mostly blows from the north, north-north-east, and north-north-west directions at a maximum mean wind speed up to 4.5 m/s coming from a northerly to a westerly direction. However, around 80% of the wind energy is produced from wind coming from the north, north-north-east, north-north-west and north-west, with the remaining wind coming from the other wind directions.

Wind energy availability and plant capacity analysis

The annual energy yield and plant capacity factors are obtained using the method explained in the “Materials and methods” section. The technical information for seven wind turbines from seven different manufacturers, but with the same rated power of 3.0 MW chosen for the estimation of wind energy yield, is given in Table 5. The wind power curves of these turbines are provided in Fig. 10. All the turbines have different rotor diameters, varying from 82.0 to 131.0 m, corresponding to turbine types WTT3 and WTT4, respectively. The cut-in speed of all the turbines is 3.0 m/s, with the exception of WTT1. Turbine WTT7 has a minimum rated speed of 10.5 m/s and is expected to produce rated power for the maximum duration relative to the other turbines. In order to obtain the net energy yield and plant capacity factors, the losses considered (11.48%) are listed in Table 6. All the energy and capacity values presented here are after considering these losses.

Table 5 Specifications of chosen 3.0 MW rated capacity pitch control turbines

Wind turbine	Rotor diameter (m)	Cut-in-speed (m/s)	Rated speed (m/s)	IEC class
WTT1	100.0	4.0	16.0	I
WTT2	91.3	3.0	12.0	II
WTT3	82.0	3.0	16.0	IA
WTT4	131.0	3.0	13.5	IIIA
WTT5	115.0	3.0	11.5	-
WTT6	112.0	3.0	11.5	-
WTT7	130.0	3.0	10.5	IIIA

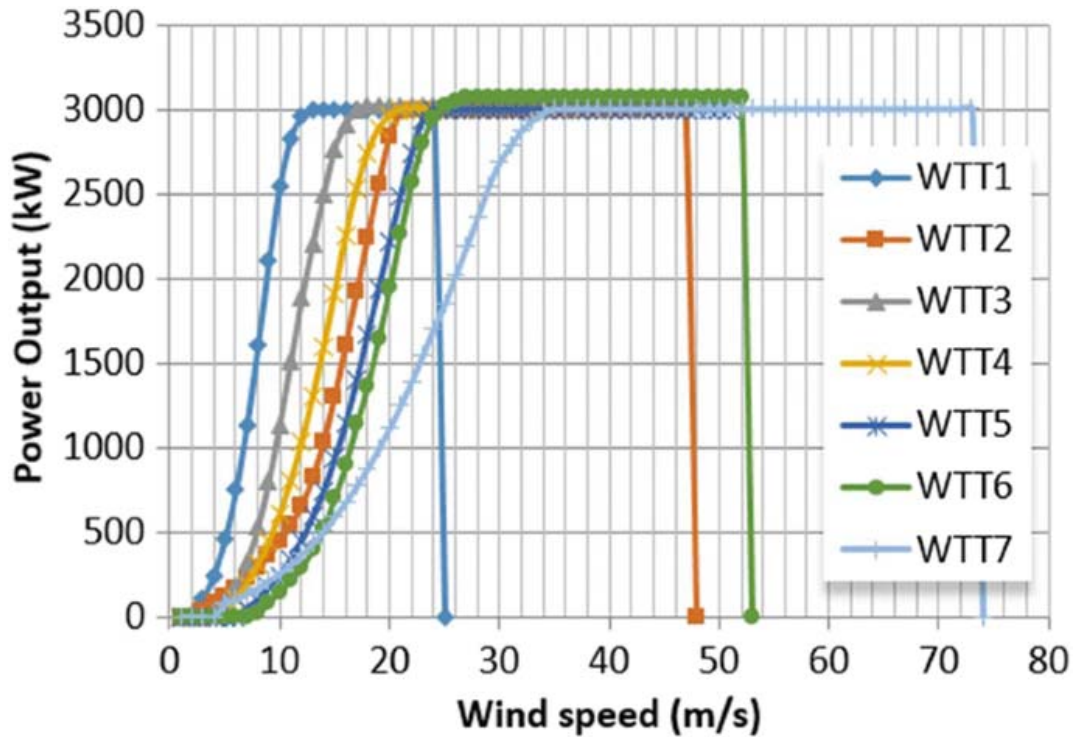


Fig. 10. Wind power curves of the turbines used in this study

Table 6. Summary of losses considered for net power calculations

Loss type	(%)
Availability	4
Wake effects	3
Turbine performance	2
Electrical	3
Total	11.48

The annual energy yield and the plant capacity factors obtained are compared for all the chosen turbines in Fig. 11 and Fig. 12, respectively. It is evident from these figures that coastal locations are much better than inland locations in terms of annual energy yield and plant capacity factor. The annual energy yield at inland sites varies from 2500.0 to 7000.0 MWh, while at coastal locations (Cape Town, East London and Port Elizabeth), it ranges from 8000.0 to around 13,500.0 MWh (Fig. 11). Similarly, the plant capacity at inland sites (Bloemfontein, Johannesburg and Pretoria) varies between 10.0 and 28.0%, while at coastal sites, it varies between 30.0 and 52.0% (Fig. 12). Where wind turbine performance is concerned, WTT4 and WTT7 performed the best, WTT5 and WTT6 performed second best and WTT1 performed third best.

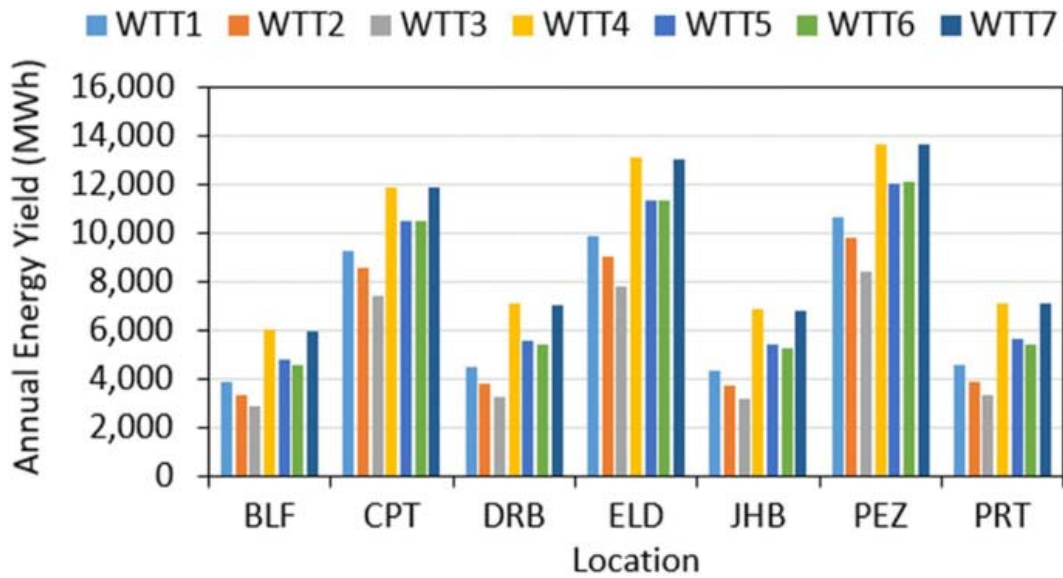


Fig. 11. Annual energy yield

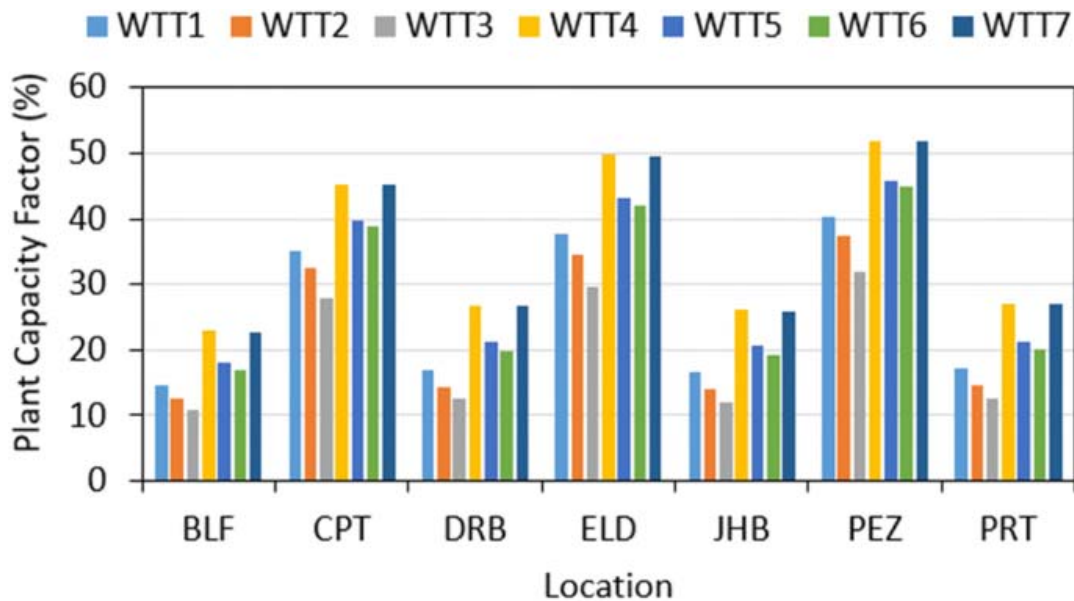


Fig. 12. Annual plant capacity factor

The magnitude (percentage of time the wind turbine does not produce power) of zero power indicates that wind speed remained below the cut-in speed of the turbine. Hence, wind turbines with a minimum possible cut-in speed are preferred for better performance (Fig. 13). On the other hand, the magnitude (percentage of time the wind turbine produces rated power) of rated power indicates that wind speed remained above the rated wind speed of the turbine (Fig. 14). So, the minimum and maximum durations of zero and rated power are the indicators of better performance of the wind turbine and better wind resources at the site under consideration.

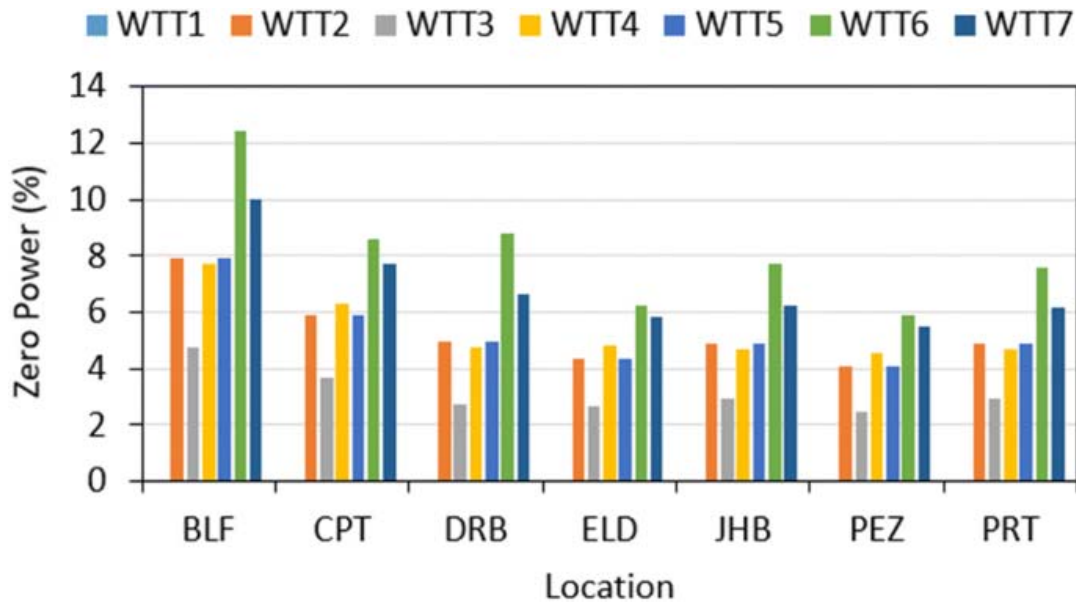


Fig. 13. Percentage of time no power produced at each site

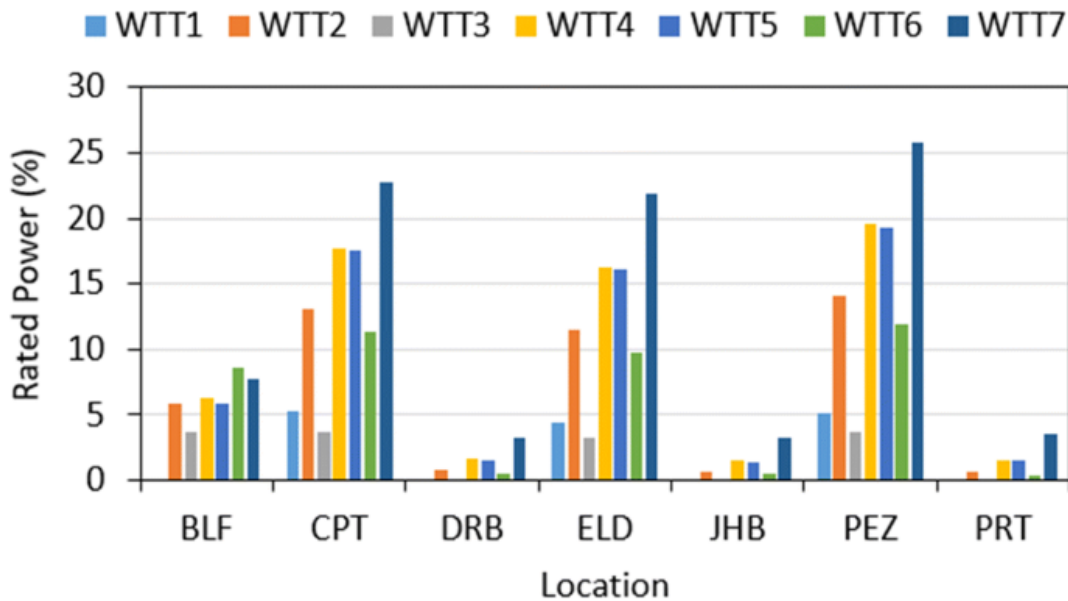


Fig. 14. Percentage of time rated power produced at each site

At coastal sites, WTT7, with zero and rated power generation durations of 7.8 and 23.0% at Cape Town, 6.0 and 22.0% at East London and 6.0 and 26% at Port Elizabeth, is recommended as the best turbine, and coincides with the highest annual energy and plant capacity values. Wind turbines WTT4 and WTT5, with zero and rated power durations of 6.0 and 17.5% at Cape Town, 4.5 and 16.0% at East London and 4.5 and 20.0% at Port Elizabeth, are recommended as the second choice, which again matches the annual energy yield and plant capacity factor values discussed earlier. Finally, WTT1 is found to be the third-best

performer in terms of zero and rated power duration values, ranging from 4.0 to 6.0% and 12.0 to 14.0% at these sites.

Keeping in mind the magnitudes of annual energy yield (Fig. 11) and plant capacity factors (Fig. 12), the coastal locations of Cape Town, East London and Port Elizabeth are technically found to be exploitable wind power sites.

Conclusions

Long-term (20 years from 2000 to 2019) hourly mean values of wind speed at 10 m above ground level were obtained for seven locations and analysed statistically to recommend potential sites for wind power development among the chosen sites. The wind speed data was extrapolated to different heights using power law with a wind shear exponent of 0.14.

The annual, monthly and diurnal wind speed variations were studied in detail. The annual energy yield and plant capacity factors, along with zero and rated power duration values, were used to recommend the best sites and the best performing wind turbines. The findings are summarised below:

- The highest mean wind speed (6.01 m/s) was noticed at Port Elizabeth and the lowest wind speed (3.86 m/s) was noticed at Bloemfontein.
- An increasing trend of wind speed with increasing latitudes was observed at the coastal sites (Cape Town, Durban, East London and Port Elizabeth), while the reverse was observed at the inland locations (Bloemfontein, Johannesburg and Pretoria).
- Rapid annual changes are seen in mean wind speed values at coastal locations.
- Relatively high winds are observed at coastal locations in relation to inland sites.
- The EPF varied between a minimum of 1.489 at Pretoria and a maximum of 1.858 at Cape Town. Higher EPF values correspond to sites with fair to good wind power potential.
- The best fit linear regression lines showed decreasing annual mean wind speed trends at most of the locations, while increasing trends were observed at Bloemfontein (+0.0002 m/s per year, Eq. 7) and Cape Town (0.0031 m/s per year, Eq. 8). The highest decreasing rate (-0.0033 m/s per year) of annual mean wind speed was observed at Pretoria.
- At Bloemfontein, Durban, Johannesburg and Pretoria, the wind power density values varied in a narrow range of 150 to 200 W/m², but at Cape Town, East London and Port Elizabeth, these values varied from 450.0 to 700.0 W/m², which is a wide range, during the entire data reporting period.
- It is worth mentioning that the change in frequency with height at coastal locations is found to be under 1.0% for each height step above 70 m. This simply means that increasing hub height further may not be useful from a wind power generation point of view.

- Based on annual energy yield, plant capacity factors, and zero and rated power durations, wind turbine WTT7 is recommended as the first choice for Cape Town, East London and Port Elizabeth. However, WTT4 and WTT5 are found to be the second choice, and WTT1 is found to be the third option.
- Finally, Cape Town, East London and Port Elizabeth are found to be good sites for wind power deployments based on the wind speed and power characteristics presented in this study.

Abbreviations

AGL: above ground level

EPF: energy pattern factor

WPD: wind power density

WT: wind turbine

Location abbreviations

BLF: Bloemfontein

CPT: Cape Town

DRB: Durban

ELD: East London

JHB: Johannesburg

PEZ: Port Elizabeth

PRT: Pretoria

Acknowledgements

Authors acknowledge the support of the Deanship of Scientific Research at King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia, for funding this work through grant number DF191002.

References

Akpinar E, Akpinar S (2005) A statistical analysis of wind speed data used in installation of wind energy conversion systems. *Energy Convers Manag* 46:515–532. <https://doi.org/10.1016/j.enconman.2004.05.002>

- Al-Abbadi NM, Rehman S (2009) Wind speed and wind power characteristics for Gassim, Saudi Arabia. *Int J Green Energ* 6:210–217. <https://doi.org/10.1080/15435070902785068>
- Assowe Dabar O, Awaleh MO, Kirk-Davidoff D, Olauson J, Söder L, Awaleh SI (2019) Wind resource assessment and economic analysis for electricity generation in three locations of the Republic of Djibouti. *Energy* 185:884–894. <https://doi.org/10.1016/j.energy.2019.07.107>
- Bagiorgas HS, Mihalakakou G, Rehman S, Al-Hadhrami LM (2012) Wind power potential assessment for seven buoys data collection stations in Aegean Sea using Weibull distribution function. *J Renew Sust Energ* 4:013119. <https://doi.org/10.1063/1.3688030>
- Bagiorgas HS, Mihalakakou G, Rehman S, Al-Hadhrami LM (2016) Wind power potential assessment for three buoys data collection stations in the Ionian Sea using Weibull distribution function. *Int J Green Energ* 13(7):703–314. <https://doi.org/10.1080/15435075.2014.896258>
- Baseer MA, Meyer JP, Alam MM, Rehman S (2015) Wind speed and power characteristics for Jubail industrial city, Saudi Arabia. *Renew Sust Energ Rev* 52:1193–1204. <https://doi.org/10.1016/j.rser.2015.07.109>
- Baseer MA, Rehman S, Meyer JP, Alam MM (2017a) GIS-based site suitability analysis for wind farm development in Saudi Arabia. *Energy* 141:1166–1176. <https://doi.org/10.1016/j.energy.2017.10.016>
- Baseer MA, Meyer JP, Rehman S, Alam M (2017b) Wind power characteristics of seven data collection sites in Jubail, Saudi Arabia using Weibull parameters. *Renew Energy* 102:35–49. <https://doi.org/10.1016/j.renene.2016.10.040>
- Bassyouni M, Gutub S, Javaid U, Awais M, Rehman S, Abdel-Hamid S, Abdel-Aziz M, Abouel-Kasem A, Shafeek H (2015) Assessment and analysis of wind power resource using Weibull parameters. *Energy Explor Exploit* 33:105–122. <https://doi.org/10.1260/0144-5987.33.1.105>
- Bosilovich M, Lucchesi R, Suarez M (2016) MERRA-2: file specification. GMAO Office Note 9:73 http://gmao.gsfc.nasa.gov/pubs/office_notes
- Fagbenle RO, Katende J, Ajayi OO, Okeniyi JO (2011) Assessment of wind energy potential of two sites in North-East. Nigeria *Renew Energ* 36:1277–1283. <https://doi.org/10.1016/j.renene.2010.10.003>
- Fant C, Adam Schlosser C, Strzepek K (2016a) The impact of climate change on wind and solar resources in southern Africa. *Appl Energy* 161:556–564. <https://doi.org/10.1016/j.apenergy.2015.03.042>
- Fant C, Gunturu B, Schlosser A (2016b) Characterizing wind power resource reliability in southern Africa. *Appl Energy* 161:565–573. <https://doi.org/10.1016/j.apenergy.2015.08.069>

- Ferrari F, Besio G, Cassola F, Mazzino A (2020) Optimized wind and wave energy resource assessment and offshore exploitability in the Mediterranean Sea. *Energy* 190:116447. <https://doi.org/10.1016/j.energy.2019.116447>
- Gough M, Lotfi M, Castro R, Madhlopa A, Khan A, Catalão JPS (2019) Urban wind resource assessment: a case study on Cape Town. *Energies* 12:1–20. <https://doi.org/10.3390/en12081479>
- Himri Y, Rehman S, Draoui B, Himri S (2008) Wind power potential assessment for three locations in Algeria. *Renew Sust Energ Rev* 12:2488–2497. <https://doi.org/10.1016/j.rser.2007.06.007>
- Himri Y, Rehman S, Agus Setiawan A, Himri S (2012) Wind energy for rural areas of Algeria. *Renew Sust Energ Rev* 16:2381–2385. <https://doi.org/10.1016/j.rser.2012.01.055>
- Himri Y, Rehman S, Himri S, Mohammadi K, Sahin B, Malik AS (2016) Investigation of wind resources in Timimoun region. *Algeria Wind Eng* 40:250–260. <https://doi.org/10.1177/0309524X16645483>
- Hulio ZH, Jiang W, Rehman S (2017) Technical and economic assessment of wind power potential of Nooriabad. *Pakistan Energ Sust Soc* 7:35. <https://doi.org/10.1186/s13705-017-0137-9>
- Hulio ZH, Jiang W, Rehman S (2019) Techno - economic assessment of wind power potential of Hawke's Bay using Weibull parameter: a review. *Energ Strat Rev* 26:100375. <https://doi.org/10.1016/j.esr.2019.100375>
- Inambao FL, Cunden K (2019) Offshore wind resource assessment off the South African coastline. *Int J Mech Eng Tech* 10:95–119
- Kazimierczuk AH (2019) Wind energy in Kenya: a status and policy framework review. *Renew Sust Energ Rev* 107:434–445. <https://doi.org/10.1016/j.rser.2018.12.061>
- Mas'ud AA, Wirba AV, Ardila-Rey JA, Albarracín R, Muhammad-Sukki F, Duque AJ, Bani NA, Munir AB (2017) Wind power potentials in Cameroon and Nigeria: lessons from South Africa. *Energies* 10:1–19. <https://doi.org/10.3390/en10040443>
- Moner-Girona M, Bódis K, Morrissey J, Kougiass I, Hankins M, Huld T, Szabó S (2019) Decentralized rural electrification in Kenya: speeding up universal energy access. *Energ Sust Dev* 52:128–146. <https://doi.org/10.1016/j.esd.2019.07.009>
- Natarajan N, Rehman S, Nandhini SS, Vasudevan M (2021) Evaluation of wind energy potential of the state of Tamil Nadu. *India based on trend analysis FME Trans* 49:244–251
- Nobela ON, Bansal RC, Justo JJ (2019) A review of power quality compatibility of wind energy conversion systems with the South African utility grid. *Renew Energ Focus* 31:63–72. <https://doi.org/10.1016/j.ref.2019.10.001>

- Penchah M, Malakooti H, Satkin M (2017) Evaluation of planetary boundary layer simulations for wind resource study in east of Iran. *Renew Energy* 111:1–10. <https://doi.org/10.1016/j.renene.2017.03.040>
- Pullinger D, Ali A, Hill N, Zhang M, Crutchley T (2019) Improving accuracy of wind resource assessment through feedback loops of operational performance data: a case study in South Africa. *J Energ South Afr* 30:1–10. <https://doi.org/10.17159/2413-3051/2019/v30i3a5669>
- Rafique M, Rehman S, Alam MM, Alhems L (2018) Feasibility of a 100 MW installed capacity wind farm for different climatic conditions. *Energies* 11(8):2147. <https://doi.org/10.3390/en11082147>
- Rehman S (2004) Wind energy resources assessment for Yanbo, Saudi Arabia. *Energy Convers Manag* 45:2019–2032. <https://doi.org/10.1016/j.enconman.2003.11.009>
- Rehman S (2005) Prospects of wind farm development in Saudi Arabia. *Renew Energy* 30:447–463. <https://doi.org/10.1016/j.renene.2004.04.008>
- Rehman S (2006) Offshore wind power assessment on the east coast. *Wind Eng* 29:409–420. <https://doi.org/10.1260/2F030952405775992643>
- Rehman S, Al-Abbadi NM (2005) Wind shear coefficients and their effect on energy production. *Energy Convers Manag* 4:62578–62591. <https://doi.org/10.1016/j.enconman.2004.12.005>
- Rehman S, Al-Abbadi NM (2007) Wind shear coefficients and energy yield for Dhahran, Saudi Arabia. *Renew Energy* 32:738–749. <https://doi.org/10.1016/j.renene.2006.03.014>
- Rehman S, Al-Abbadi NM (2008) Wind shear coefficient, turbulence intensity and wind power potential assessment for Dhulom, Saudi Arabia. *Renew Energy* 33:2653–2660. <https://doi.org/10.1016/j.renene.2008.02.012>
- Rehman S, Al-abbadi N (2010) Wind power characteristics on the north west coast of Saudi Arabia. *Energ Env* 20:1257–1270. <https://doi.org/10.1260/0958-305X.20/21.8/1.1257>
- Rehman S, Halawani TO, Mohandes M (2003) Wind power cost assessment at twenty locations in the Kingdom of Saudi Arabia. *Renew Energy* 28:573–583. [https://doi.org/10.1016/S0960-1481\(02\)00063-0](https://doi.org/10.1016/S0960-1481(02)00063-0)
- Rehman S, Ahmad A, El-Amin I, Al-Hadhrami LM (2009) Assessment of wind power, wind exponent, local air density and air turbulence intensity for an isolated site. *Int J Sust Energ* 28:217–230. <https://doi.org/10.1080/14786450903221511>
- Rehman S, Ahmad A, Al-Hadhrami LM (2011) Development and economic assessment of a grid connected 20 MW installed capacity wind farm. *Renew Sust Energ Rev* 15:833–838. <https://doi.org/10.1016/j.rser.2010.09.005>

Rehman S, Mahbub Alam AM, Meyer JP, Al-Hadhrami LM (2012) Wind speed characteristics and resource assessment using Weibull parameters. *Int J GreenEnergy* 9(8):800–814. <https://doi.org/10.1080/15435075.2011.641700>

Rehman S, Mohandes MA, Alhems LM (2018) Wind speed and power characteristics using LiDAR anemometer based measurements. *Sust Energy Tech Assess* 27:46–62. <https://doi.org/10.1016/j.seta.2018.03.009>

Rehman S, Natarajan N, Vasudevan M, Alhems L (2020a) Assessment of wind energy potential across varying topographical features of Tamil Nadu India. *Energy Explor Exploit* 38:175–200. <https://doi.org/10.1177/0144598719875276>

Rehman S, Natarajan N, Mohandes AM, Alam MM (2020b) Latitudinal wind power resource assessment along the coastal areas of Tamil Nadu, India. *FME Transactions* 48:566–575

Shoaib M, Siddiqui I, Rehman S, Ur Rehman S, Khan S (2017) Speed distribution analysis based on maximum entropy principle and Weibull distribution function. *Environ Prog Sustain Energy* 36:1480–1489. <https://doi.org/10.1002/ep.12589>

Shoaib M, Siddiqui I, Rehman S, Khan S, Alhems L (2019) Assessment of wind energy potential using wind energy conversion system. *J Clean Prod* 216:346–360. <https://doi.org/10.1016/j.jclepro.2019.01.128>

Sterl S, Liersch S, Koch H, Lipzig NPNV, Thiery W (2018) A new approach for assessing synergies of solar and wind power: implications for West Africa. *Environ Res Lett* 13:1–11. <https://doi.org/10.1088/1748-9326/aad8f6>

Touafio NJF, Sanda O, Malenguinza S, M’Boliguipa J, Mouangue RM (2020) Analysis of a wind turbine project in the city of Bouar (Central African Republic). *Sci Afr* 8:e00354. <https://doi.org/10.1016/j.sciaf.2020.e00354>

Ucar A, Balo F (2009) Evaluation of wind energy potential and electricity generation at six locations in Turkey. *Appl Energy* 86:1864–1872. <https://doi.org/10.1016/j.apenergy.2008.12.016>

Weblink 1 (2020) Wind Energy International (WWEA), Weblink. <https://library.wwindea.org/global-statistics/> (accessed May 13, 2020).

Weblink 2 (2020) Wind Power Monthly, Weblink <https://www.windpowermonthly.com/article/1663058/wind-set-bulk-new-south-african-capacity-2030> (accessed May 9, 2020).

Wright MA, Grab SW (2017) Wind speed characteristics and implications for: wind power generation: Cape regions, South Africa. *South Afr J Sci* 113:1–