Latitudinal Wind Power Resource Assessment Along Coastal Areas of Tamil Nadu, India

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Globally, the wind power capacities are growing every passing year, which is an indicative of social and commercial acceptance of this technology by a larger section of the populations. In Indian perspective, the wind power capacities are also increasing with annual additions of new capacities and most of the development work is taking place in the southern part and that too in Tamil Nadu state. Research work in the area of accurate wind power assessment is being conducted to optimize the utilization of wind power and at the same time efforts are being exerted to enhance the operation and maintenance capabilities of the local skilled and semi-skilled work force. This study utilizes 38 years of hourly mean wind speed data from seven locations for providing the accurate wind power assessment and understanding the longitudinal behavior of its characteristics. The wind speed is found to be increasing with decreasing latitudes and having lesser variation in wind direction fluctuations, simply means conversing wind direction to narrower bands. Kanyakumari is identified as the most probable wind power deployment site with annual energy yield of 227.55 MWh and capacity factor of 34% followed by Vedaranyam, and Thoothukudi, as second and third priority sites with respective annual yields of 223.36 MWh and 218.73 MWh.

Keywords: *Wind power; resource assessment; Weibull distribution; Latitudinal variation*

1. INTRODUCTION

Traditional power resources are swiftly diminishing, so there is an immediate demand for new, clean, and self renewing sources of energy. These fossil fuels are being used increasingly for power generation in different parts of the globe which is causing adverse climatic changes. Hence to control the adverse climatic changes, people from all walks of life are eager to use fuels which can promote sustanable life on the planet. The new and renewable sources of energy which are being encourged in different parts of the world include wind, solar photo-voltaic, solar thermal, hydro, wave, geothermal, biofuels, biomass, and biofuels. Of these, wind power is being used widely due to its commercial and technological acceptance. On the technological evolution, wind turbines are available in few kilowatt to multi-megawatt sizes, easy and economical to maintain, very minimal time for installation after resources assessment, and compatible cost of energy per kilowatt hour [1,2].

Global wind power installed capacity is increasing continuously and reached 650.758 GW at the end of 2019, an increase of 10% compared to 2018 (591.091 GW), [3]. The top five countries in terms of cumulative installed capacity include China, United States of America, Germany, India and Spain with respective contributions of 251.029, 105.433, 61.357, 37.529, and 25.808 GW. Wind speed, among the meteorological parameters, is a highly fluctuating parameter and its proper long-term understanding is critical from profitable wind power harnessing point of view. Accordingly, numerous studies have been conducted in diffent countries to conduct the wind power resource assessments before going for actual wind farm deployments.

Fazelpour et al. [4] analysed the wind power sources and conducted economical feasibilty to minimize the investment risk in Zabol, Zahak, Zahedan, and Mirjaveh cities in Sistan and Balouchestan districts of Iran. They discovered that Zabol and Zahedan were better sites for profitable power generation. Allouhi et al. [5] assessed the wind power capacity at 6 coastal areas in Morocco. The study revealed that Dakhla was the most appropriate site for wind power deployment in the area, while the next best site was Laayoune. Zhao et al. [6] evaluated the impact of priority dispatch of wind power on energy conservation and concluded that energy intensity decreased as wind power penetration increased. Becerra et al. [7] provided a techno-economic analysis for 90 kW small wind power systems for two Chiliean locations for power generation. Aukitino et al. [8] accomplished wind power source evaluations for Tarawa and Abaiang cities in Kiribati. The study stated that a wind farm with 5 wind turbines each of 275 kW rated capacities can recover the investment in a time period of 5.42 to 8.74 years.

Souloukngа et al. [9] examined wind resources assessment for Faya-Largeau in the Saharan area of Chad by utilizing data over a period of 18 years (1960-

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1978) at 10 m elevation and recommended a wind turbine of 1.5 MW rated power to be most suitable for power generation at the proposed site. Qing [10] carried out an analytical evaluation of the wind features in Santiago Island and suggested a wind power curve which can be made use of to identify the unpredictability of power generation arising from the wind speed fluctuations. Jung et al. [11] examined the capacity of 6 onshore wind farms sites to meet national and global power intake based on ERA-20C information. The research concluded that 98 nations can satisfy their existing electrical requirements wind power installed density of 0.0734MW/m^2. Additionally, such a set up can allow 73 nations to cover 100% electrical energy intake. Ouarda et al. [12] checked out the wind power possibility making use of uniform and heterogeneous mix circulations to model wind speed information in a north area of Nordic. They ended up that the mixed circulations offered better fit than the standard one-component circulations for the location.

Rafique et al. [13] performed feasibility study of 100MW installed capacity wind farms at 5 cities in Saudi Arabia and reported that all the sites were feasible for wind power generation with Dhahran being the most suitable. Hulio et al. [14] examined the wind power availability at Nooriabad site in Pakistan and reported mean wind power densities of 169.4 and 416.7 W/m^2 at 30m and 50m above ground level. Arreyndip et al. [15] evaluated the wind power capacity of 3 of Cameroon's coastal cities (Kribi, Douala, and also Limbe) for the growth of wind farms by using NASA's monthly mean wind data for 31 years. They reported Kribi as one of the most ideal site for wind farm deployment based upon the mean power density, most probable wind speed, and also maximum energy carrying wind speed. Rasuo et al. [16,17] presented a method for determination of optimum positions of single wind turbines within a wind farm installed to achieve maximum production using genetic algorithm as an optimization technique. In another study, Rasuo et al. [18] presented the harmonization of new wind turbine rotor blades development as well as the analysis and verification of a wind turbine rotor blade made of composite materials. Researchers interested in further reading on various aspects of performance evaluation and improvement of wind turbine blades are referred to [19-23].

Wind power advancement in India started in the 1990s and has grown at faster pace in the last couple of years. The domestic planning of wind power in India has led the nation to end up being the 4th biggest wind power generator worldwide (Laudari et al. [24]). Since June 2018, the cumulative wind power installed capability of India was 34.293 GW [25]. Tamil Nadu (TN) has constructed wind power capacity of 11.113 GW. TN, being a seaside state, so it observes high winds for 6 months moderate for 4 months around the year.

Globally, several studies have been carried out for wind power evaluation along seaside locations. Howerver, such studies are very limited with regards to coastal location in India in general and Tamil Nadu in particular. In this paper, the wind power resources assessment is carried out for 7 sites, situated along the seaside. The present study utilizes hourly mean values of wind speed and other meteorological variables. This study provides synthesized mean wind speed at different hub heights, latitudinal variation of the mean wind speed, annual variation of the mean wind speed over the entire data collection period, latitudinal variation of the wind direction and wind speed frequency, Weibull distribution parameters, annual wind turbine performance, monthly total energy production, mean capacity factor, and diurnal variability of net energy availability.

2. STUDY AREA AND DATA DESCRIPTION

The objective of this research is to evaluate the wind power capacity of 7 sites situated along seaside in Tamil Nadu, India. The sites chosen for the study are Chennai, Mahabalipuram, Cuddalore, Vedaranyam, Velankanni, Thoothukudi, and Kanyakumari. The map revealing these cities (in black rectangle-shaped boxes) is provided in Figure 1.

Chennai is situated on the south-eastern coastline a flat plain. The altitude of Chennai is around 6.7 m. The area has trees, and three to four storeyed structures. Mahabalipuram is situated on the seaside at 12.62°N as well as 80.19°E. The surface of these sites is covered with grass and is open on the north side. Cuddalore is situated at an altitude of 6 m over MSL and is a flat land with huge deposits of black and alluvial soils. Vedaranyam is situated at 10.37°N 79.85°E and is 1 m above MSL. The topography is normally flat and gently inclined towards the sea. Velankanni goes along Bay of Bengal. The topography is basically flat with average altitude of 15.85m. Thoothukudi is positioned in the Gulf of Mannar about 125km north of Cape Commorin and is mainly a levelled surface. Kanyakumari lies in the southerly tip at an altitude of 300m AMSL.

The summary of the site-specific details (geographical coordinates, long-term mean ambient temperature, pressure, air density ratio, wind speed, wind power density, etc) is provided in Table 1. Wind speed data scanned every three seconds at 50 m above ground level (AGL) was saved as hourly average. The wind speed and other parameters were obtained from [26] for a period of 38 years i.e. from January 1980 to December 2017 at the seven meteorological stations. There were no missing observations in the recorded data.

Table 1 shows that the pressure level and air density are almost similar for all the locations. The maximum wind speed of 6.41m/s is observed at Vedaranyam, followed by Kanyakumari with 6.37m/s, and Thoothukudi with 6.31m/s. The wind power density is highest at Kanyakumari (211W/m^2) and lowest at Chennai (127W/m^2) [column 9, Table 1]. The wind power class is poor at Chennai, Mahabalipuram, Cuddalore, and Velankani while marginal at Vedaranyam, Thoothukudi and Kanyakumari. The surface roughness (SRF) and roughness class (RFC) are the same for all the locations. The mean wind speed over the entire dataset was calculated at different heights of 60 m, 70 m, 80 m, 90 m, 100 m, 110 m and 120 m respectively (Table 2). The mean wind speed is highest at Vedaranyam and lowest at Chennai at all the heights above ground level. At different heights, the mean wind speed is highest at Vedaranyam, followed by Kanyakumari, Thoothukudi, Velankanni, Mahabalipuram, Cuddalore and Chennai.

Table 1. Site dependent geographical and meteorological data

Location	LAT °N	LON °E	TMP °C	PR kPa	AD Kg/m^3	DR	WS50 m/s	WPD50 W/m^2	WPC	SD
Chennai	13.000	80.000	28.1	100.3	1.141	0.931	5.40	127	Poor	2.01
Mahabalipuram	12.627	80.193	27.9	100.6	1.139	0.930	5.67	146	Poor	2.09
Cuddalore	11.748	79.771	28.0	100.5	1.138	0.929	5.60	140	Poor	2.03
Velankanni	10.682	79.844	27.6	100.8	1.143	0.933	6.22	187	Poor	2.16
Vedaranyam	10.372	79.851	27.4	100.8	1.144	0.934	6.41	206	Marg	2.54
Thoothukudi	08.764	78.135	27.3	100.6	1.143	0.933	6.31	200	Marg	2.31
Kanyakumari	08.088	77.539	27.0	100.3	1.156	0.943	6.37	211	Marg	2.40

Table 2. Measured and synthesized mean wind speed (m/s) over entire data collection period.

Location	WS120	WS110	WS100	WS90	WS80	WS70	WS60	WS50
Chennai	6.11	6.03	5.95	5.87	5.77	5.66	5.54	5.40
Mahabalipuram	6.40	6.33	6.24	6.15	6.05	5.94	5.81	5.67
Cuddalore	6.34	6.26	6.18	6.09	5.99	5.88	5.75	5.60
Velankanni	7.03	6.94	6.85	6.75	6.64	6.52	6.38	6.22
Vedaranyam	7.25	7.16	7.06	6.96	6.85	6.72	6.58	6.41
Thoothukudi	7.14	7.05	6.96	6.86	6.74	6.62	6.48	6.31
Kanyakumari	7.21	7.12	7.02	6.92	6.81	6.68	6.54	6.37

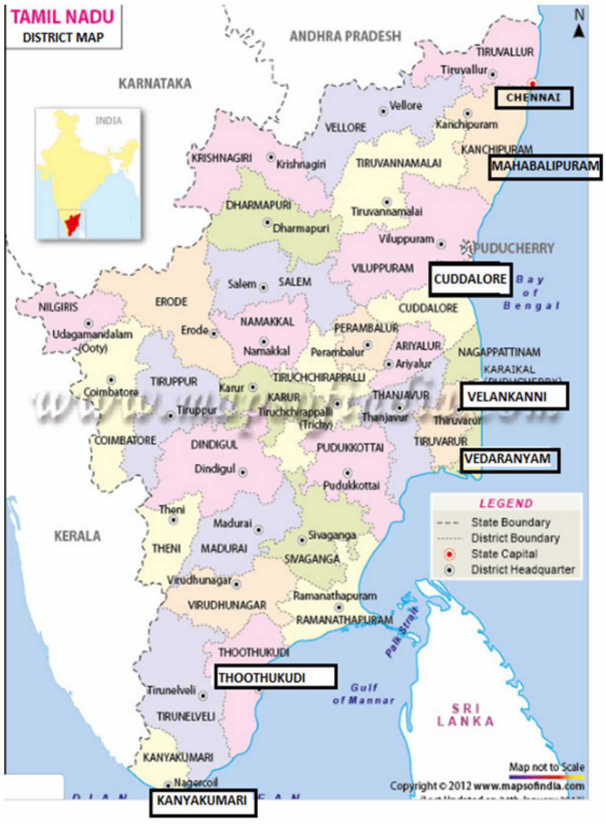


Figure 1. Location map of the sites used for wind power resources assessment

3. METHODOLOGY

The distribution of the wind speed frequency distribution is very important in evaluating the potential of the wind speed of a particular location. There are many distribution functions to describe the wind speed frequency curve such as Weibull, Rayleigh, Lognormal, etc. but the most commonly used distribution is the Weibull distribution. The two-parameter Weibull distribution function is used to determine the effectiveness of the wind potential [27-32]. The Weibull function is given by the probability density function f(v) as [33]:

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

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 be termed as V_{mean}. The mean and variance of the wind speed are expressed as follows:

$$V_{mean} = \frac{1}{N}\sum_{i=1}^{N} V_i \tag{2}$$

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

The wind power can be calculated using the following equation [34]:

$$P_w = \frac{1}{2}\rho A_T V^3 \tag{4}$$

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 Weibull probability density function as follows [35]:

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

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 [36]:

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

4. RESULTS AND DISCUSSION

In this study, the latitudinal wind power assessment has been carried out at seven coastal sites as mentioned earlier. The latitudinal variation of the mean wind speed at 50 m and 120 m AGL is shown in Figure 2. A linear regression analysis was also carried out and the best fit line is also included in Figure 2. It is observed that Chennai at highest latitude of 13°N has the least mean wind speed and Kanyakumari and Thoothukudi which are south of Chennai at 8.764°N and 8.088°N latitudes possess higher mean wind speeds. As the latitude increases, the mean wind speed decreases. The best-fit linear regression line shows that the wind speed increases by 0.1785m/s with each degree of latitude increment. The coefficient of determination of around 84% further strengthens the usefulness of the regression line for the estimation of wind speed at different latitudes. Thus, it may be attributed that latitudinal variation of the wind speed should also be considered while selecting a potential site for wind power capacity built up.

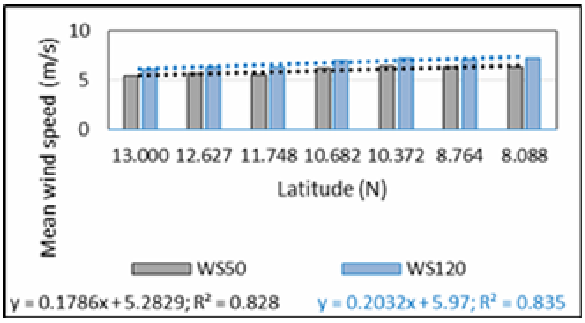


Figure 2. Latitudinal variation of mean wind speed at 50 and 120 m

4.1 Long-Term Wind Speed Trends

The annual mean wind speed values from 1980 to 2017 are shown in Figure 3 along with the linear re gression lines at different locations. The annual mean wind speed trends at of Chennai (13.000°N), Mahabalipuram (12.627 °N), and Cuddalore (11.748°N) are similar as the latitudes of these stations are in close proximity. The Mahabalipuram and the Cuddalore trends are similar compared to Chennai. Kanyakumari is located at 8.088 °N, down south and has larger variations in wind speed values compared to above three locations in the north throughout the reporting period from 1980-2017. The profiles of Vedaranyam and Velankanni situated at 10.682°N and 10.372°N are almost alike in terms of trends but different in magnitudes. The profile of Thoothukudi is more similar to Kanyakumari as the latitude of Thoothukudi (8.764°N) is closer to Kanyakumari.

The linear regression best fit line coefficients along with the coefficient of determination (R^2) values are summarized in Table 3. Decreasing trends of wind speeds are observed at majority of the locations except at Thoothukudi and Kanyakumari where slightly increasing trends are observed over the years. The coefficient of determination values are very low but still an approximate idea of annual mean wind speeds trends over the coming years can be drawn for future wind power resource assessment.

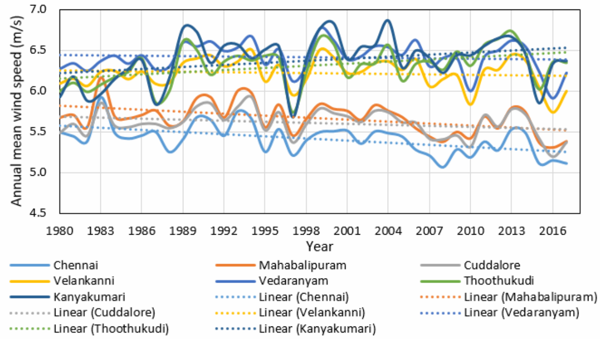


Figure 3. Annual variation of mean wind speed over entire data collection period (1980-2017)

This analysis assures (i) that wind aped is related with the latitude of the location, (ii) decreasing wind speed trends at most of the locations over the years of data analysis, (iii) a promising fact that the annual mean wind speed is always above 5 m/s at all the locations till 2017, and (iv) and two bands or ranges of mean wind speed based on latitudes (13.000 to 10.372 and 10.682 to 08.088°N) can be seen from Figure 3. Hence at some of these sites, the wind power development could more feasible economically than others.

Table 3. Best fit equation for different stations based on annual mean wind speed

Station	Linear best fit equation	R²
Chennai	y = -0.0106x + 26.517	0.3353
Mahabalipuram	y = -0.0085x + 22.614	0.2532
Cuddalore	y = -0.0042x + 13.952	0.0822
Velankanni	y = -0.002x + 10.185	0.0168
Vedaranyam	y = -0.0015x + 9.4306	0.0092
Thoothukudi	y = 0.0087x - 11.116	0.1892
Kanyakumari	y = 0.0077x - 9.1083	0.0951

4.2 Latitudinal Dependence of Wind Direction

The prevailing wind direction and availability of the harness able wind energy is important for wind power project developers and it can be understood well using wind rose diagrams which is also known as finger prints of the wind speed. Figure 4 shows the variation in availability of wind speed from different wind direction over entire data collection period at all the seven sites considered in this study. At a glance, it can be said that as the latitude decreases, meaning as one move southwards, the incoming wind direction spread tend to merge in narrow wind direction ranges. For example, at Chennai the wind is coming from all directions and is prevalent from north east and from south west directions (Figure 4a).

At Mahabalipuram, the wind speed distribution is almost the same but with more spread towards the west (Figure 4b). As one moves further down to Cuddalore, the wind direction becomes more narrow and most of the wind blows from north south and south west directions (Figure 4c). At Thoothukudi and Kanyakumari, most of winds blow from the west direction (Figure 4f and Figure 4g). The wind direction spread becomes very small and most of the wind is obtained from a very narrow wind speed band at these locations. These two sites are expected to have least wind turbulence and better for normal operating life of the wind turbines. It is evident from this analysis that wind direction at these sites is also dependent of the latitude of the location. As one moves downwards to south, the wind direction spread keeps on converging.

4.3 Wind Speed Frequency Distribution

It is important for the wind industry to be able to describe the variation of wind speeds. Furthermore, turbine designers need the information to optimize the design of the turbines to minimize the costs of energy generation. The two parameter Weibull distribution is a good approximation for the wind speed distribution. The scale parameter 'c' is a measure of the characteristic wind speed of the distribution and is proportional to the mean wind speed.

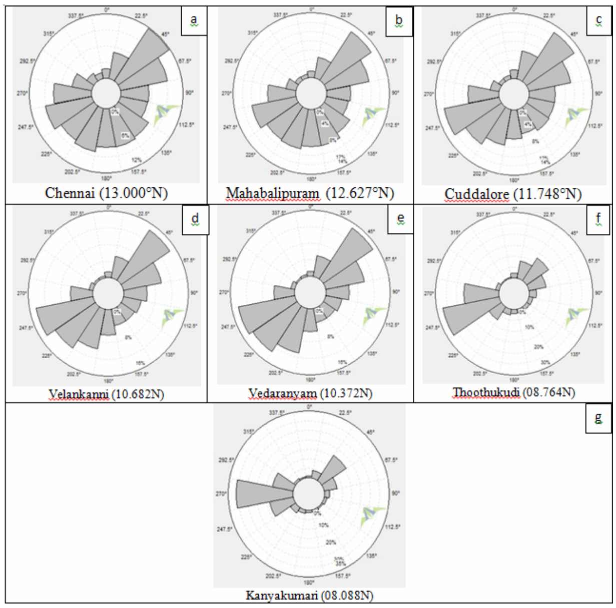


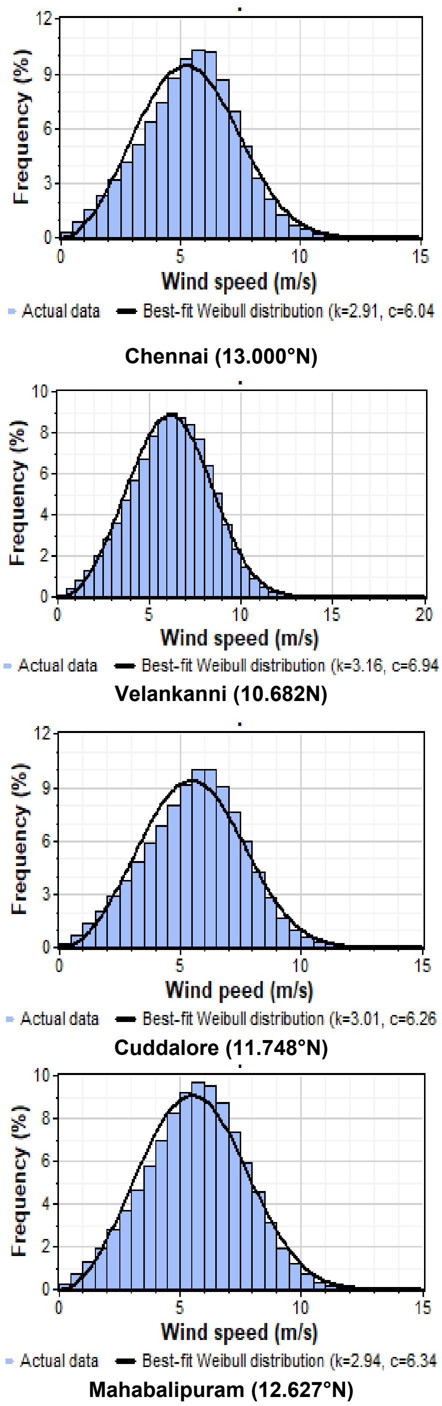
Figure 4. Latitudinal variation of wind direction and wind speed frequency distribution

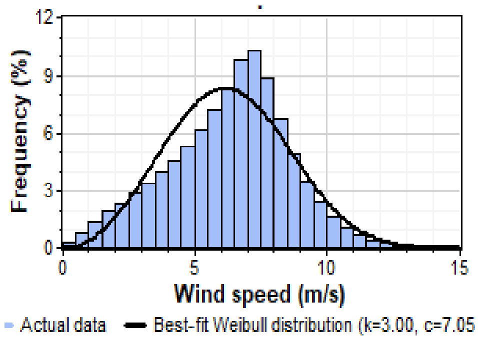
The shape parameter 'k' specifies the shape of a Weibull distribution and varies between 1.5 and 3.5. A small value of 'k' represents highly variable winds, while constant winds are characterized by a larger value of k. In reality, the wind speed varies continuously and in order to be able to predict a wind turbine's energy output it is necessary to know exactly how often the wind blows and how strongly. Normally, the wind is measured with an anemometer and the mean wind speed is recorded every 10 minutes. This data then can be sorted into wind speed bins of 1 m/s each. The energy contained in the wind at a certain site may then be expressed by this frequency distribution. In the present case, the hourly mean values of the wind speed over entire data collection period from all the sites are used to find the Weibull parameters and then the frequency distributions are plotted in Figure 5. The values of the Weibull parameters are summarized in Table 4.

The scale parameters values are also observed to be increasing with decreasing latitudes like wind speed. Larger values of 'c' ~7m/s are observed Velankanni to Kanyakumari and around 6 m/s north of Velankanni. In general, the shape parameter values are found to be ~ 3. The Weibull distribution is seen to be normally fitted with measured wind speed values for first five stations viz., Chennai, Mahabalipuram, Cuddalore, Velankanni, and Vedaranyam. However, the distribution does not fit well for Kanyakumari and Thoothukudi.

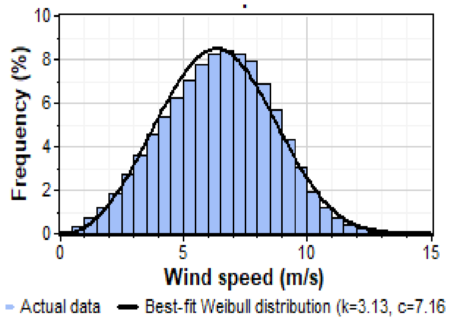
Table 4. Weibull Scale and shape parameters for the stations

Location	Weibull parameters		
	Scale (c)	Shape (k)	R^2
Chennai	6.04	2.91	0.976
Mahabalipuram	6.34	2.94	0.988
Cuddalore	6.26	3.01	0.979
Velankanni	6.94	3.16	0.992
Vedaranyam	7.16	3.13	0.990
Thoothukudi	7.05	3.00	0.929
Kanyakumari	7.13	2.93	0.927

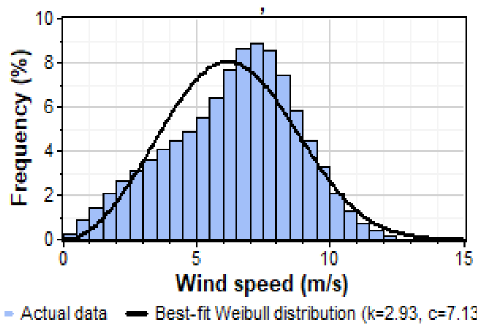




Thoothukudi (08.764N)



Vedaranyam (10.372N)



Kanyakumari (08.088N)

Figure 5. Wind speed frequency distribution at 50 m

4.4 Energy Yield Estimation

The annual wind turbine performance results based on entire data collection period are shown in Table 5. Wind speed at hub height of 120m (it is the height where the hub of the rotor is installed) is highest at Vedaranyam (7.25m/s) and lowest at Chennai (6.11m/s). The rotor diamater, the cut-in-speed, and the rated speed of the chosen wind turbine are 90.0m, 3.0m/s, and 13.0m/s; respectively. The duration during which the turbine was idle is higher than the duration at which the turbine was running at rated power. The zero power output is highest (4.08%) at Chennai and lowest (1.9%) at Vedaranyam. The net power estimated was highest at Kanyakumari (672.8kW) and lowest at Chennai (427.2kW). The net annual estimated energy production was also highest at Kanyakumari (5894MWh/yr) and lowest at Chennai (2743MWh/yr). Similar observation was found for the net capacity factor variation. In general, an increasing trend is observed in net power, annual energy yield, and the capacity factor with decreasing latitudes or as moving southwards from north.

The monthly total energy production over the entire data collection period is seen to be highest in the month of June at all the locations and the lowest in the month of February and March, (Table 6). The estimated total energy production, over entire data reporting period, is highest at Kanyakumari (227.55GWh) and lowest at Chennai (143.87GWh).

The variation in the total energy output over the months is analogous at all the locations. The total monthly energy output decreases in February and then it shows an increasing trend from March until June and then a decreasing trend from July to October. The energy output again increases from November to December. In general, the power requirements are found to be more during summer compared to wintertime and the hence the available wind power can be utilized optimally based on load following characteristics. The plant capacity factor do varies with the month of the year but has highest values in the months of June and July (Table 7). At Velankanni, Vedaranyam, Thoothukudi, and Kanyakumari; the plant capacity factors reached to more than 50% in June and July, as listed in Table 7. The overall capacity factors remained above 20% at all the locations as can be seen from the last row of Table 7. Sites situated in the lower latitudes tend to possess more mean capacity factors compared to the sites in the higher latitudes.

The diurnal energy yield trends dictate higher energy availability during daytime from 10:00 to 18:00 hours (Table 8), which matches with the higher load requirements due to larger cooling loads in the daytime. The number of hours during which high energy production is observed increases as one moves from the higher to the lower latitudes. The chosen wind turbine produces more than 7GWh of power for 5 hours from 12:00 to 16:00 hours in the day. Similarly, at Mahabalipuram, Cuddalore, Velankanni, Vedaranyam, Thoothukudi , and Kanyakumari the energy is produced or available for 11, 8, 20, 24, 23, and 24 hours of the day, respectively.

Stations situated in the higher latitudes have lower capacity to generate electricity throughout the day compared to the stations situated in the lower latitudes.

Table 5. Annual wind turbine performance results

Location	Hub Height	Percentage of time		Mean		
	Wind Speed (m/s)	Zero Power	Rated Power	Net Power (kW)	Net AEP (MWh/yr)	NCF (%)
Chennai	6.11	4.08	0.03	427.2	3743	21.36
Mahabalipuram	6.40	3.32	0.05	486.3	4260	24.31
Cuddalore	6.34	3.46	0.02	471.6	4131	23.58
Velankanni	7.03	2.06	0.03	611.6	5358	30.58
Vedaranyam	7.25	1.90	0.04	660.4	5785	33.02
Thoothukudi	7.14	3.60	0.02	646.7	5665	32.34
Kanyakumari	7.20	3.72	0.02	672.8	5894	33.64

Table 6. Monthly total energy production over entire data collection period

	Net Monthly Total Energy Output (GWh)						
Month	Chennai	Mahabalipuram	Cuddalore	Velankanni	Vedaranyam	Thoothukudi	Kanyakumari
Jan	9.49	11.74	13.50	18.39	20.15	20.34	23.80
Feb	7.00	7.43	8.34	11.37	12.52	12.34	12.86
Mar	8.72	8.08	7.44	8.25	8.63	7.39	7.05
Apr	11.49	11.47	8.80	8.60	8.92	7.24	7.59
May	15.16	17.95	15.82	20.40	22.77	21.30	21.08
Jun	16.48	19.92	20.62	28.30	30.57	30.99	30.17
Jul	15.89	18.59	18.60	25.71	26.81	30.77	30.84
Aug	13.71	15.58	15.09	22.48	24.18	27.13	27.83
Sep	7.84	9.58	9.41	15.48	18.05	20.22	21.76
Oct	7.52	8.28	7.62	9.97	11.30	11.23	12.56
Nov	14.41	16.44	14.76	15.54	16.01	10.40	10.31
Dec	16.17	19.40	19.48	22.37	23.43	19.37	21.68
Overall	143.87	164.46	159.49	206.85	223.36	218.73	227.55

Table 7. Monthly mean capacity factor (%) over entire data collection period

	Net Monthly Mean Capacity Factor (%)						
Month	Chennai	Mahabalipuram	Cuddalore	Velankanni	Vedaranyam	Thoothukudi	Kanyakumari
Jan	16.35	20.23	23.27	31.69	34.72	35.05	41.01
Feb	13.24	14.05	15.77	21.50	23.67	23.33	24.32
Mar	15.02	13.92	12.82	14.22	14.88	12.73	12.15
Apr	20.46	20.43	15.67	15.32	15.88	12.90	13.52
May	26.12	30.93	27.27	35.15	39.24	36.71	36.33
Jun	30.11	35.47	36.71	50.38	54.43	55.19	53.71
Jul	28.09	32.03	32.06	44.30	46.21	53.02	53.15
Aug	24.24	27.55	26.69	39.75	42.77	47.97	49.22
Sep	14.32	17.51	17.20	28.28	32.99	36.95	39.77
Oct	13.30	14.65	13.47	17.64	19.99	19.86	22.21
Nov	26.34	30.04	26.97	28.40	29.25	19.00	18.84
Dec	28.59	34.31	34.46	39.56	41.44	34.27	38.35
Overall	21.36	24.31	23.58	30.58	33.02	32.34	33.64

Table 8. Diurnal variability of net energy availability during entire data collection period

	Net Hourly Total Energy Production (GWh)						
Hour	Chennai	Mahabalipuram	Cuddalore	Velankanni	Vedaranyam	Thoothukudi	Kanyakumari
00:00	4.86	6.47	5.62	7.53	8.32	7.30	8.73
01:00	4.64	6.13	5.46	7.35	8.00	6.91	8.43
02:00	5.18	6.32	6.00	7.70	8.09	7.99	8.97
03:00	5.88	6.63	6.51	7.95	8.19	9.15	9.60
04:00	5.86	6.43	6.33	7.71	7.98	9.21	9.83
05:00	5.49	5.92	5.83	7.24	7.60	9.01	9.91
06:00	5.21	5.44	5.35	6.78	7.23	8.85	9.92
07:00	5.15	5.17	5.10	6.52	7.03	8.84	9.96
08:00	5.33	5.16	5.10	6.53	7.10	8.99	10.04
09:00	5.63	5.38	5.32	6.85	7.49	9.45	10.34
10:00	5.95	5.74	5.67	7.41	8.14	10.01	10.61
11:00	6.31	6.22	6.07	8.09	8.91	10.40	10.46
12:00	7.16	7.09	6.94	9.05	9.84	10.81	9.94
13:00	7.81	7.88	7.96	10.09	10.78	11.14	9.56
14:00	7.72	8.21	8.41	10.66	11.36	10.87	9.28
15:00	7.38	8.31	8.54	10.88	11.63	10.40	9.00
16:00	7.01	8.28	8.46	10.87	11.70	9.93	8.85
17:00	6.68	8.21	8.29	10.76	11.66	9.50	8.90
18:00	6.40	8.12	8.05	10.58	11.52	9.14	9.08
19:00	6.16	7.99	7.75	10.30	11.24	8.82	9.27
20:00	5.96	7.84	7.42	9.93	10.86	8.54	9.41
21:00	5.66	7.54	6.92	9.34	10.25	8.16	9.35
22:00	5.35	7.18	6.40	8.67	9.54	7.79	9.16
23:00	5.10	6.83	5.98	8.06	8.89	7.52	8.95
Overall	143.87	164.46	159.49	206.85	223.36	218.73	227.55

5. CONCLUSION

In this study, the hourly mean wind speed data from seven coastal sites of the state of Tamil Nadu, India was used for the accurate wind power assessment and understanding of the longitudinal behavior of the wind speed characteristics. The conclusions based on this study are as follows:

- The maximum mean wind speed of 6.41m/s is observed at Vedaranyam, followed by Kanyakumari and Thoothukudi.
- The wind power density is highest at Kanyakumari (211W/m^2) and least at Chennai (127W/m^2).
- The mean wind speed at different heights of 60m, 70m, 80m, 90m, 100m, 110m and 120m above ground level is the highest at Vedaranyam and lowest at Chennai.
- Chennai with the highest latitude of 13^{o}N has the least mean wind speed and Kanyakumari and Thoothukudi which are south of Chennai at 8.764^{0}N and 8.088^{o}N latitudes possess higher mean wind speed. Thus, latitudinal variation of the wind speed should be definitely considered during the selection of a potential site for wind power generation.
- Decreasing trends of annual mean wind speeds are observed at majority of the locations except at Thoothukudi and Kanyakumari where slightly increasing trends are observed over the years.
- Windrose plots indicate that Kanyakumari and Thoothukudi have the least wind turbulence which is better for normal operation of the wind turbines.
- Similar to the wind speed behavior, the Weibull scale parameter values also increase with decreasing latitudes.
- An increasing trend is observed in net power, annual energy yield, and the capacity factor with decreasing latitudes or from north to south.
- The estimated total energy production, over entire data reporting period, is highest at Kanyakumari (227.55GWh) and lowest at Chennai (143.87GWh). Sites situated in the lower latitudes tend to possess more mean capacity factors compared to the sites in the higher latitudes.
- The number of hours during which high energy production is observed increases as one moves from the higher to the lower latitudes. At Mahabalipuram, Cuddalore, Velankanni, Vedaranyam, Thoothukudi, and Kanyakumari the energy is produced or available for 11, 8, 20, 24, 23, and 24 hours of the day, respectively.

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REFERENCES

[1] Baseer, M.A., Meyer, J.P., Rehman, S., Alam, Md. M.: Wind power characteristics of seven data collection sites in Jubail, Saudi Arabia using Weibull parameters. Renew. Energ., Vol. 102, 35-49, 2017.

[2] Rehman, S., Ahmad, A.: Assessment of wind energy potential for coastal locations of the Kindgom of Saudi Arabia. Energy, Vol. 29, No. 8, 1105-1115, 2004.

[3] https://www.statista.com/statistics/217522/cumulative-installed-capacity-of-wind-power-worldwide/ (Accessed on May 03, 2020)

[4] Fazelpour, F., Markarian, E., Soltani, N.: Wind energy potential and economic assessment of four locations in Sistan and Balouchestan province in Iran. Renew. energ., Vol. 109, 646-667, 2017.

[5] Allouhi, A. et al.: Evaluation of wind energy potential in Morocco's coastal regions. Renew. Sust. Energy. Rev., Vol. 72, 311-324, 2017.

[6] Zhao, X., Liu, S., Yan, F., Yuan, Z., Liu, Z.: Energy conservation, environmental and economic value of the wind power priority dispatch in China. Renew. Energ., Vol. 111, 666-675, 2017.

[7] Becerra, M., Moran, J., Jerez, A., Cepeda, F., Valenzuela, M.: Wind energy potential in Chile: Assessment of a small scale wind farm for residential clients. Energy convers. Manag. , Vol. 140, 71-90, 2017.

[8] Aukitino, T., Khan, M.G.M., Ahmed, M.R., 2017. Wind energy resource assessment for Kiribati with a comparison of different methods of determining Weibull parameters. Energy convers. Manag. 151, 641-660.

[9] Soulouknga, M.H. et al.: Analysis of wind speed data and wind energy potential in Faya-Largeau, Chad using Weibull distribution. Renew. energ., Vol. 121, 1-8, 2018.

[10] Qing, X.: Statistical analysis of wind energy characteristics in Santiago island, Cape Verde. Renew. energ., Vol. 115, 448-461, 2018.

[11] Jung, C., Schindler, D., Laible, J.: National and global wind resource assessment under six wind turbine installation scenarios. Energy convers. Manag., Vol. 156, 403-415, 2018.

[12] Ouarda, B.M.J.T., Charron, C.: On the mixture of wind speed distribution in a Nordic region. Energy convers. Manag., Vol. 174, 33-44, 2018.

[13] Rafique, M.M. et al.: Feasibility of a 100MW installed capacity wind farm for different climatic conditions. Energies, Vol. 11, No. 8, 2147, 2018a.

[14] Hulio, Z.H., Jiang, W., Rehman, S.: Technical and economic assessment of wind power potential of Nooriabad, Pakistan. Energy Sustain. Soc., Vol. 7, No. 1, 35, 2017.

[15] Arreyndip, N.A., Joseph, E., David, A.: Wind energy potential assessment of Cameroon's coastal regions for the installation of an onshore wind farm. Energies, Vol. 2, 1-19, 2016.

[16] Rasuo, B., Bengin, A.: Optimization of Wind Farm Layout, FME Trans., Vol. 38, No 3,107-114, 2010a.

[17] Rasuo, B., Bengin, A., Veg, A.: On Aerodynamic Optimization of Wind Farm Layout, Proceedings in Applied Mathematics and Mechanics, Vol. 10, No. 1, 539–540, 2010b.

[18] Rasuo, B., Dinulovic, M., Veg, A., Grbovic, A., Bengin, A.: Harmonization of new wind turbine rotor blades development process: A review, Renewable and Sustainable Energy Reviews, Vol. 39, 874-882, 2014.

[19] Ouarda, B.M.J.T., Charron, C.: On the mixture of wind speed distribution in a Nordic region. Energy convers. Manag., Vol. 174, 33-44, 2018.

[20] Bakic, V., Pezo, M., Stojkovic, S.: Technical and economic analysis of grid-connected PV/WIND energy stations in Serbia under varying climatic conditions. FME Trans., Vol. 44,71-82, 2016.

[21] Mohammed, B., Abdullah, O.I., Al-Tmimi, A.I.: Investigation and Analysis of Wind Turbines Optimal Locations and Performance in Iraq, FME Trans., Vol. 48,155-163, 2020.

[22] Svorcan, J., Trivković, Z., Ivanov, T., Baltić, M., Peković, O.: Multi-objective Constrained Optimizations of VAWT Composite Blades Based on FEM and PSO, FME Trans., Vol. 47, No. 4, pp. 887-893, 2019.

[23] Biadgo, A.M., Aynekulu, G.: Aerodynamic Design of Horizontal Axis Wind Turbine Blades. FME Trans., Vol. 45, 647-660, 2017.

[24] Laudari, R., Sapkota, B., Banskota, K.: Validation of wind resource in 14 locations in Nepal. Renew. Energ, Vol. 119, 777-786, 2018.

[25] Global statistics, Global wind energy council. Retrieved 23 May 2016.

[26] Bosilovich, M. G., R. Lucchesi, and M. Suarez, 2016: MERRA-2: File Specification. GMAO Office Note No. 9 (Version 1.1), 73 pp, available from http://gmao.gsfc.nasa.gov/pubs/office_notes

[27] Bagiorgas, H.S., Mihalakakou, G., Rehman, S., Al-Hadhrami, L.M.: Weibull parameters estimation using four different methods and most energy carrying wind speed analysis. International Journal of Green Energy, Vol. 8, No. 5, 529 – 554, 2011.

[28] Bagiorgas, H.S., Mihalakakou, G., Rehman, S., Al-Hadhrami, L.M.: Wind Power Potential Assessment for Seven Buoys Data Collection Stations in Aegean Sea Using Weibull Distribution Function. Journal of Renewable and Sustainable Energy, Vol. 4, No. 1, 013119-013134, 2012.

[29] Rehman, S., Mahbub, A.M., Meyer, J.P., Al-Hadhrami, L.M.: Wind Speed Characteristics and Resource Assessment using Weibull Parameters. International Journal of Green Energy, Vol. 9, 800-814, 2012.

[30] Bassyouni, M., Saud, A.G., Javaid, U., Awais, M., Rehman, S., Abdel-Hamid, S.M.S., Abdel-Aziz, M.H., Abouel-Kasem, A., Shafeek, H.: Assessment and analysis of Wind Power Resource using Weibull Parameters. Energy Exploration & Exploitation, Vol. 33, No. 1, 105 – 122, 2015.

[31] Bagiorgas, H.S., Mihalakakou, G., Rehman, S., Al-Hadhrami, L.M.: Wind Power Potential Assessment for Three Buoys Data Collection Stations in Ionian Sea Using Weibull Distribution Function. International Journal of Green Energy, Vol. 13, No. 7, 703-714, 2016.

[32] Shoaib, M.,Siddiqui, I., Rehman, S., Saifur, R., Khan, S.: Speed Distribution Analysis based on Maximum Entropy Principle and Weibull Distribution Function. Environmental Progress & Sustainable Energy, Vol. 36, No. 5, 1480-1489, 2017.

[33] Akpinar, E.K., Akpinar, S.: A statistical analysis of wind speed data used in installation of wind energy conversion systems. Energ. Convers. Manag., Vol. 46, No. 4, 515-532, 2005.

[34] Penchah, M.M., Malakooti, H., Satkin, M.: Evaluation of planetary boundary layer simulations for wind resource study in east of Iran. Renew. Energ. , Vol. 111, 1-10, 2017.

[35] Ucar, A., Balo, F.: Evaluation of wind energy potential and electricity generation at six locations in Turkey. Appl. Energ., Vol. 86, 1864-1872, 2009.

[36] Keyhani, A., Abbaszadeh, R.: An assessment of wind energy potential as a power generation source in the capital of Iran, Tehran. Energy, Vol. 35, No. 1, 188-201, 2010.

NOMENCLATURE

LAT	Latitude
LON	Longitude
TMP	Mean temperature
PR	Mean pressure
AD	Mean air density
DR	Air density ratio
Marg	Marginal
WS	Mean wind speed
WS50	Wind speed at 50 m
WS60	Wind speed at 60 m
WS70	Wind speed at 70 m
WS80	Wind speed at 80 m
WS90	Wind speed at 90 m
WS100	Wind speed at 100 m
WS110	Wind speed at 110 m
WS120	Wind speed at 120 m
WPD	Wind power density
WPD50	Wind power density at 50 m
WPC	Wind power class
RFC	Roughness class
SRF	Surface roughness
SD	Standard deviation

РЕСУРС ЛАТИТУДИНАЛНОГ ВЕТРА У ПРИОБАЛНОМ ПОЈАСУ ДРЖАВЕ ТАМИЛ НАДУ У ИНДИЈИ

С. Рехман, Н. Натараџан, М.А. Мохандес, Мд.М. Алам

Ветрогенератори се широм света из године у годину све више користе што показује да ову технологију у социјалном и комерцијалном погледу прихвата све већи број становника. У Индији се капацитети ветрогенератора повећавају сваке године и највише се

развијају на југу, посебно у држави Тамил Наду. У тој држави се врше истраживања прецизне процене енергије ветра у циљу оптимизације њеног искоришћавања и унапређивања квалитета рада локалне квалификоване и полуквалификоване радне снаге у функционисању и одржавању капацитета. У раду су коришћени подаци о просечној брзини ветра на час прикупљени са седам локација у периоду од 38 година како би се добила прецизна процена енергије ветра и боље разумело лонгитудинално понашање његових карактеристика. Утврђено је да се брзина ветра повећава са опадањем географске ширине и да има мање варијација у правцу кретања ветра, што значи да се креће према ужим појасевима. Локација Канјакумари је одређена за потенцијално место коришћења енергије ветра са годишњим енергетским приносом од 227,55 MWh и фактором капацитета 34%. Друга и трећа локација по прио-ритету су Ведаранјам и Тотхукуди са годишњим енергетским приносом од 223,36 MWh односно 218,73 MWh.