Wind Power Resources Assessment Under Varying Topography

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1 Introduction

The growing concern of environmental pollution and awareness among people from all walks of life has lead the researchers, developers, engineers, and even the politicians to think about new, clean renewable sources of energy to combat the increasing concentrations of greenhouse gases in the atmosphere.

Depletion of conventional energy sources and environmental sustainability issues have created challenges for researchers and policy makers to explore and discover renewable energy sources such as solar, wind, geothermal, tidal, biogas, biomass, biofuels, etc. Among these, wind energy has become a promising source due to its competitive nature abundance, ease of harvesting, inexhaustible and affordable resources [1, 2]. Irrespective of irregularities existing in the global renewable energy market, the overall installed capacity of wind power has increased over 104% during the last decade [3]. It is evident from the increasing global wind power capacities (591.5 GW end 2018 with new addition of 51.3 GW and increase of 10.9% compared to 2017) that it is a well-established technology.

For the development of wind power at any location, statistical analysis of wind data serves as a key tool for assessing wind energy potential [2]. Extensive studies have been conducted on wind characteristics and wind power potential in many countries around the world [4–12].

To accentuate the importance of evaluation of wind energy potential, a few studies have been briefly mentioned here. Alaydi [13] analyzed the wind data at two sites in the Gaza strip in Rafah and recommended for wind energy exploitation. Ajayi et al. [14] assessed the potential of wind resources in Jos, Nigeria for power generation based on the monthly mean wing speeds of 1987–2007 and concluded that Jos was a suitable site for wind farm projects. Allouhi et al. [15] evaluated the potential of wind energy for six coastal locations in Morocco and that Dakhla was the most suitable location for harnessing the wind power while Laayoune the second suitable site.

In the Indian context, wind power development in India has gained momentum over the last few decades. Ramachandra et al. [16] evaluated the wind energy availability and its characteristics in the Uttara Kannada district of Karnataka and concluded that coastal taluks such as Karwar and Kumta have good wind energy potential. Ganesan and Ahmed [17] reported annual energy yields of 3.712 GWh and 4.431 GWh corresponding to hub heights of 50 and 70 m for Bhopal in India. In another interesting study, Singh and Prakash [18] evaluated the availability of wind energy for electricity production at Ranchi, Jamshedpur, Devghar, Lohardaga, and Chaibasa in Jharkhand, India, and reported that the sites were unsuitable for wind power generation on a large scale. Phadke et al. [19] reported Tamil Nadu as one of the potential states for harvesting 95% of the nation's wind energy potential.

In this paper, wind characteristics and energy potential of three cities, namely Chennai, Erode, and Coimbatore, located at different elevations above mean sea level, with different topographical features and distances from the shore, have been

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studied. Specifically, the study provides the diurnal variation of the mean wind speed, wind directional analysis, wind speed probability distribution, monthly and annual mean variation of the wind speed, wind energy yield, and capacity factors using five different wind turbines of 2.0 MW rated capacities. Although several studies have been reported on the potentiality of the wind speed as a direct indicator of wind power density, studies considering the combined effect of topography, that is, distance from the shore and the elevation are limited. This study is the first attempt of its kind, where the combined effect of the above factors has been considered in estimating the wind energy potential of a location.

2 Study Area and Data Description

The study focuses on analyzing the wind power potential of cities located in the Tamil Nadu State of India. The cities considered for the study are Chennai, Coimbatore, and Erode located at 6m, 183m, and 411m above mean sea level (MSL). The map showing the locations of these cities (in rectangular boxes) is provided in Fig. 1. The summary of the site-specific details (geographical coordinates, data collection period, long-term mean ambient temperature, pressure, and air density) is provided in Table 1. The wind speed and other parameters were used for a period of 38 years (January 1980 to June 2018).

3 Results and Discussion

The wind speed characteristics (site-dependent, annual, monthly, and diurnal scales) over a long period of almost 38 years are analyzed and discussed in the following sub-sections. These characteristics include the wind speed, wind power density, energy yield, and plant capacity factor using 5 wind turbines each of 2.0 MW rated power.

3.1 Long-Term Variation at Three Sites

The long-term average wind speed values at 50 m above ground level over the entire data collection period at Chennai, Erode, and Coimbatore are compared in Table 2. As one moves away from the coastal site (Chennai) toward inland (Erode and Coimbatore), the mean wind speed decreases. Also, the mean maximum wind speed of 21.42 m/s is found at Chennai over the data collection period and a mean minimum of 13.97 m/s at Erode. A maximum wind power density of 129 W/m² is obtained for Chennai and a minimum of 76 W/m² for Erode. The mean energy content for the three cities is 1127 kWh/m²/year for Chennai, 666 kWh/m²/year for Erode, and 849 kWh/m²/year for Coimbatore. The energy pattern factor varies from 1.418 to 1.705. The higher values of mean wind speed, wind power density, and mean energy content at Chennai may be due to its being the coastal site which is open to sea on the eastern side and is also relatively flat land. The above parameter values are the least at Erode measurement site, may be due to inland location though having gentle topographic features. However, Coimbatore station is relatively better as far as wind characteristics are concerned though locked by mountains in the north and south and to a certain extent in the west as well.

Higher magnitudes of 6.0 m/s and more are found to be more prevalent from northeast and southwest directions at the Chennai data collection station (Fig. 2). The analysis also reflected that more than 50% times the wind blows from southwest direction and around 30% of the times from north-east at Chennai. At Erode station, the higher magnitude winds between 5.0 m/s and 6.0 m/s blow from west-south and west-north directions. At Coimbatore, wind speeds of 5.0 m/s to 6.0 m/s blow from the west and west-south directions. It is evident from the analysis that wind speed remained around 70%, 60%, and 70% between 4.0 m/s and 8.0 m/s at Chennai, Erode, and Coimbatore, respectively. This means that wind power can be generated at these sites above these percentages of times.

3.2 Long-Term Annual Variation

The annual variation of wind speed over a longer period and other parameters are important to have confidence on the annual availability of wind for power generation. At Chennai, the annual mean wind speed varied between a minimum of 5.1 m/s in 2008 and a maximum of 5.9 m/s in 1983 while remained around 5.2 m/s during most of the years (Fig. 3). At Erode station,

Fig. 1 Locations of the three sites used for wind power resources assessment

Table 1 Site-dependent data summary

Variable	Location		
	Chennai	Erode	Coimbatore
Latitude	N 13.000	N 11.5000	N 11.000
Longitude	E 80.000	E 77.5000	E 76.875
Elevation (m)	6	183	411
Start date	1/1/1980	1/1/1980	1/1/1980
Distance from sea shore (km)	10	227	318
End date	6/1/2018	6/1/2018	6/1/2018
Mean temperature (°C)	27.9	26.2	24.4
Mean pressure (kPa)	100.3	96.23	94.93
Mean air density (kg/m^3)	1.152	1.102	1.104
Power density at 50m (W/m^2)	129	76	97
Wind power class	1-(Poor)	1-(Poor)	1-(Poor)

Table 2 Wind speed sensor summary

Variable	Location		
	Chennai	Erode	Coimbatore
Mean wind speed (m/s)	5.40	4.34	4.70
Median wind speed (m/s)	5.49	4.15	4.55
Max wind speed (m/s)	21.42	13.97	15.50
Mean power density (W/m²)	129	76	97
Mean energy content (kWh/m²/yr)	1,127	666	849
Energy pattern factor	1.418	1.705	1.694
Data recovery rate (%)	100	100	100
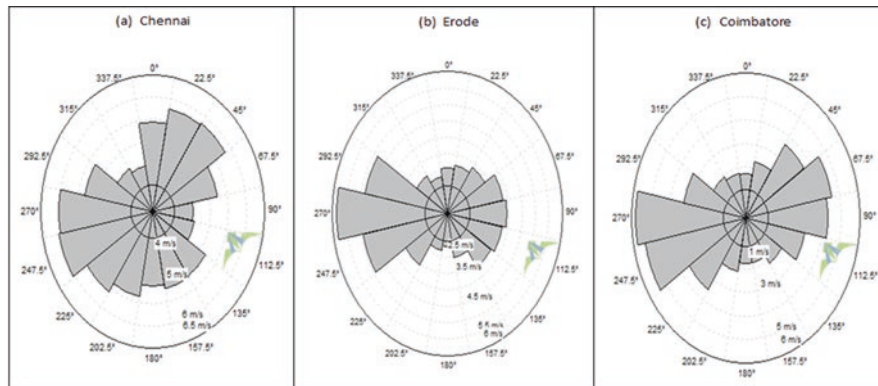
Fig. 2 Example of directional variation of long mean wind speed at Chennai station
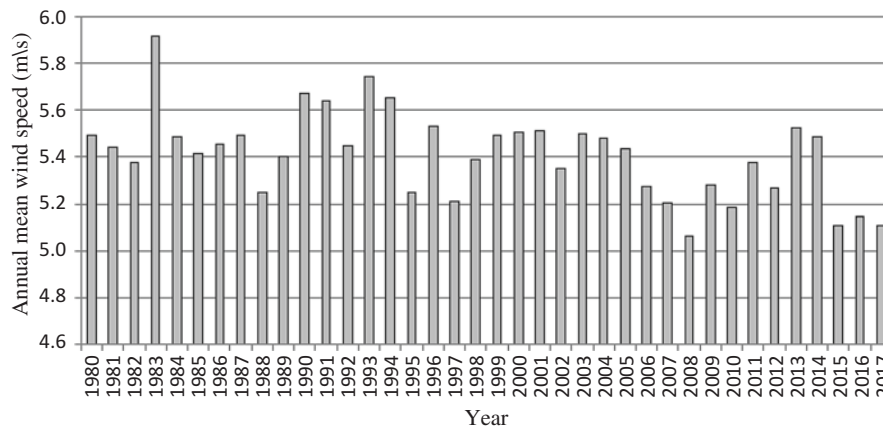
Fig. 3 Long-term mean wind speed variation at Chennai, an example

the annual mean wind speed showed a consistent behavior with minimum and maximum wind speeds of 4.0 m/s and 4.5 m/s. At Coimbatore the wind speed always remained more than 4.4 m/s with a minimum of 4.3 m/s in 2015 and a maximum of 5.1 in 1990.

3.3 Long-Term Monthly Variation

For the quality of power and grid stability management, the knowledge of the monthly variation of mean wind speed over an extended period is important. Monthly mean wind speed is found to increase from January to mid of the year, reaching a maximum of 6.23 m/s in June, and then decreased toward the end of the year at Chennai (Table 3). The overall mean wind

Table 3 Monthly mean values of all the meteorological parameters at Chennai (1980–2018)

Data column	Units	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	All
Speed_50m	m/s	4.95	4.57	4.85	5.48	5.85	6.23	6.06	5.72	4.63	4.43	5.92	6.14	5.4
Direction_50m	°	60.4	97.9	140	161	193	242	246	246	228	61.3	41.3	43.9	164
Temperature_2m	^{0}C	23.9	25.6	28.3	30.6	31.6	30.4	29.5	28.9	28.3	27.3	25.6	24.2	27.8
Pressure_0m	kPa	101	101	101	100	100	99.9	99.9	100	100	100	101	101	100
Air Density	kg/m^3	1.17	1.17	1.15	1.14	1.13	1.14	1.14	1.14	1.15	1.15	1.16	1.17	1.15
Speed_50m WPD	W/m^2	95	78	87	117	159	185	172	143	85	82	165	173	129

speed of 5.4 m/s is observed over the entire data collection period. At Erode and Coimbatore, the maximum wind speeds were observed in the month of July (6.35 m/s) and June (6.94 m/s), respectively. The highest values of WPD of 185 W/m^2, 190 W/m^2, and 234 W/m^2 were observed at Chennai (June), Erode (July), and Coimbatore (June), respectively.

3.4 Long-Term Diurnal Variation

Knowledge of diurnal changes in mean wind speed over extended periods is critical to match the peak load on the grid. At Chennai, the diurnal mean wind speed shows two peaks, one in the early morning at 4 o'clock and the other at 14:00 hours in the early afternoon (Fig. 4). So, if the local peaks occur at these timings, then this diurnal wind profile can be best utilized to supplement the peak load through wind power. At Erode, there is a clean-cut peak wind availability at around 15:00 hours which could also best utilized for peak load saving through wind power if the peak load also occurs at this time. However, there is a flat peak between 5:00 and 12:00 hours at Coimbatore which could be best utilized for flat load demands during this specific duration.

3.5 Wind Power Generation and Capacity Factor Analysis

In order to study the power generation and capacity factor, five wind turbines, each of 2.0 MW rated capacity and pitch controlled type, are chosen. The technical specifications of the chosen turbines are summarized in Table 4. For calculating the net energy generation and net capacity factor calculations, various equivalent losses of 11.4527% (availability 2%, wake effect 4%, turbine performance 2%, electrical 0%, environmental 2%, curtailment 0%, and others 2%) are considered.

Annual energy yields and capacity factors are calculated using the site-specific wind speed and wind turbine technical data. Wind turbines WT3 and WT5 produced the highest energy while WT1 and WT4 produced lesser energy at Chennai. Wind turbine WT2 performed the worst compared to the other four turbines. Almost same performance is observed at Erode and Coimbatore (figures are not included). Highest capacity factors are obtained in 1983 and the lowest in 2008, irrespective of the turbine type.

The average annual energy yield of > 3000 MWh over the entire data reporting period is obtained at Chennai based on turbines WT1, WT3, WT4, and WT5 (Fig. 5). Similarly, the higher capacity factors between 17 and 19% are obtained at Chennai corresponding to the same turbine types as above while at Erode the capacity factors remained around 10% (Fig. 6). However, at Coimbatore, the capacity factor values remained between 12 and 14%. In terms of turbine performance, WT3 and WT5 produced the maximum energy at all the locations. In terms of location performance, Chennai is found to be the best, Coimbatore the second best while Erode the least performer.
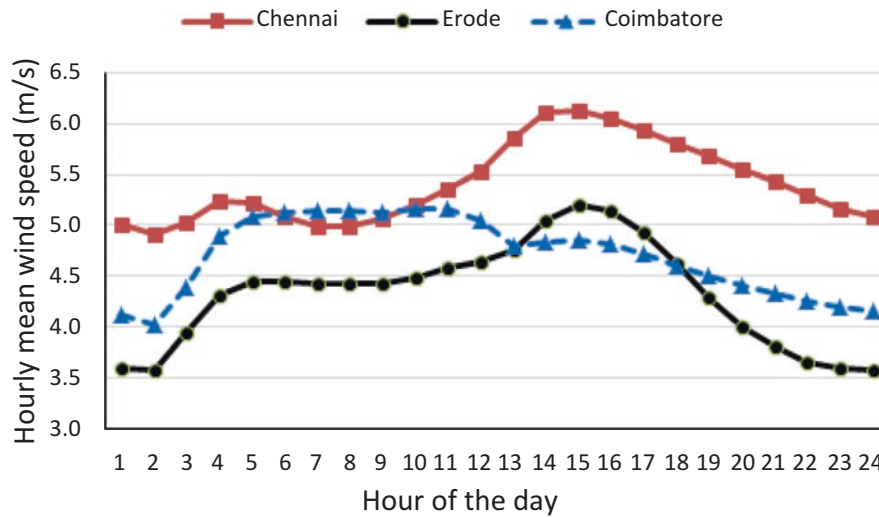
Fig. 4 Diurnal variation long-term hourly mean wind speed at three locations

Table 4 Technical specifications of pitch controlled 2.0 MW rated capacity wind turbines

Wind turbine generic names	Rotor diameter (m)	Cut-in speed (m/s)	Rated speed (m/s)
WT1	82	4	15
WT2	80	3	13
WT3	90	3	14
WT4	87	3	13
WT5	93.3	3	11.2
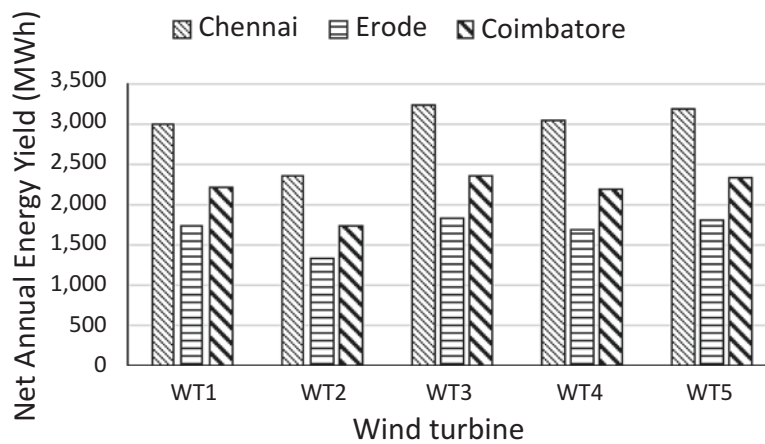
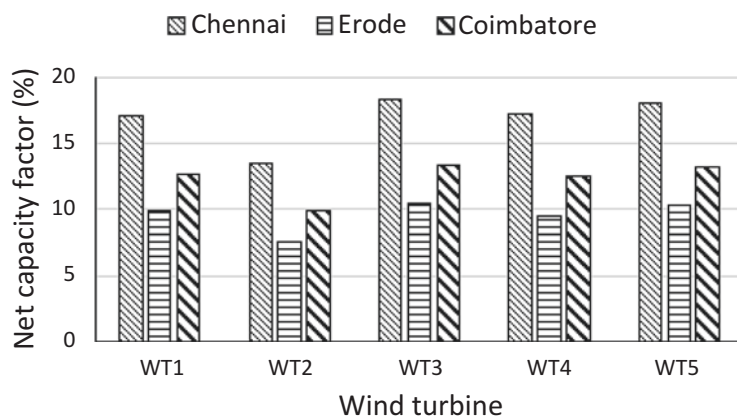**Fig. 5** Annual energy yield

Fig. 6 Annual capacity factor

4 Conclusions

For the wind resource characterization, 38 years of wind data was statistically (diurnal, monthly, and annual wind speed) analyzed. The mean wind speed for Chennai, Erode, and Coimbatore are 5.4 m/s, 4.34 m/s, and 4.7 m/s while the mean maximum are 21.42 m/s, 13.97 m/s, and 15.50 m/s. The wind speed decreases for cities located inland. The mean wind power density for Chennai, Erode, and Coimbatore are 129W/m2, 76 W/m2, and 97 W/m2 and the mean energy content 1127 kWh/m2/year, 666 kWh/m2/year, and 849 kWh/m2/year. The mean wind speed remained around 70%, 60%, and 70% between 4m/s and 8 m/s at Chennai, Erode, and Coimbatore.

The monthly variation of the mean wind speed showed an increasing trend from Jan to mid of the year and a decreasing trend toward the end of the year at all the locations. The peak frequency of wind speed is observed between 5 m/s and 6 m/s at Chennai, between 4m/s and 5 m/s at Erode and Coimbatore. Highest capacity factors are obtained in 1983 and the lowest in 2008 irrespective of the type of turbine. In terms of turbine performance, WT3 and WT5 produced the maximum energy at all the locations. Chennai is found to the best site for wind energy development followed by Coimbatore and Erode has the least prospects.

References

1. Baker JR (2003) Features to aid or enable self-starting of fixed pitch low solidity vertical axis wind turbines. J Wind Energ Ind Aerodyn 15:369–380
2. Rehman S, Ahmad A (2004) Assessment of wind energy potential for coastal locations of the Kingdom of Saudi Arabia. Energy 29(8):1105–1115
3. Global Wind Report (GWEC). Available online: http://www.gwec.net/wp-content/uploads/vip/GWEC_PRstats2016_EN_WEB.pdf. Accessed on 20 Apr 2019
4. Kose R (2004) An evaluation of wind energy potential as a power generation source in Kutahya, Turkey. Energ Conver Manage 45:1631–1644
5. Rehman S, Halawnai T, Mohandes M (2003) Wind power cost assessment at twenty locations in the Kingdom of Saudi Arabia. Renew Energy 28:573–583
6. Rehman S, El-Amin IM, Ahmad F, Shaahid SM, Al-Shehri AM, Bakhashwain JM (2007) Wind power resource assessment for Rafha, Saudi Arabia. Renew Sustain Energy Rev 11:937–950
7. Al-Abbadi NM (2005) Wind energy resource assessment for five locations in Saudi Arabia. Renew Energy 30:1489–1499
8. Elamouri M, Ben AF (2008) Wind energy potential in Tunisia. Renew Energy 33:758–768
9. Oyedepo SO, Adaramola MS, Paul SS (2012) Analysis of wind speed data and wind energy potential in three selected locations in south-east Nigeria. Int J Energy Environ Eng 3:1–23
10. Baseer MA, Meyer JP, Rehman S, Alam M (2015) Wind power characteristics of seven data collection sites in Jubail, Saudi Arabia using Weibull parameters. Renew Energy 102:35–49
11. Rehman S, Ahmed MA, Mohamed MH, Al-Sulaiman FA (2017) Feasibility study of the grid connected 10 MW installed capacity PV power plants in Saudi Arabia. Renew Sustain Energy Rev 80:319–329
12. Rafique MM, Rehman S, Alam M, Alhems LM (2018a) Feasibility of a 100 MW installed capacity wind farm for different climatic conditions. Energies 11(8):2147
13. Alaydi JY (2011) Assessment of wind energy potential in Gaza strip. Front Energy 5(3):297–304
14. Ajayi OO, Fagnenle RO, Katende J, Okeniyi JO (2011) Availability of wind energy resource potential for power generation at Jos, Nigeria. Front Energy 5(4):376–385
15. Allouhi A, Zamzoum O, Islam MR, Saidur R, Kousksou T, Jamil A, Derouich A (2017) Evaluation of wind energy potential in Morocco's coastal regions. Renew Sustain Energy Rev 72:311–324
16. Ramachandra TV, Subramanian DK, Joshi NV (1997) Wind energy potential assessment in Uttara Kannada district of Karnataka, India. Renew Energy 10(4):585–611
17. Ganesan S, Ahmed S (2008) Assessment of wind energy potential using topographical and meteorological data of a site in Central India (Bhopal). Int J Sustain Energy 27(3):131–142
18. Singh R, Prakash O (2018) Wind energy potential evaluation for power generation in selected districts of Jharkhand. Energy Sources Part A 40(6):673–679
19. Phadke A, Bharvirkar R, Khangura J (2012) Wind potential estimates for India: economic and policy implications. Environ Energy Technol Division, Berkley Lab Report:1–24