



# **Wind Energy Potential Assessment of Great Cumbrae Island Using Weibull Distribution Function**

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### **Authors' contributions**

*This work was carried out in collaboration between both authors. Author EYK designed the study, performed the statistical analysis and wrote the first draft of the manuscript. Author JM managed the analysis of the study. Both authors read and approved the final manuscript.*

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## **ABSTRACT**

Wind energy is among the fastest growing energy generation technology which is highly preferred alternative to conventional sources of energy. The major Scottish Government target is to deliver 30% of her energy demand by 2020 from renewable sources of energy as well as meeting the emission targets as set under the Scotland Climate Change Act 2009. In this paper, wind energy potential assessment of Great Cumbrae Island was investigated. For this, a ten year mean monthly wind speed at height 50 m obtained from the National Aeronautic Space Administration (NASA) were analysed using the Weibull probability distributions to assess the wind energy potential of Great Cumbrae Island as a clean, sustainable energy resource. Results from the wind-speed model showed that Great Cumbrae Island as high wind-speed site with a mean wind speed of 7.598 m/s and having power density 483.50 W/m<sup>2</sup>. The annual energy captured by four selected horizontal wind turbine models was determined. The result shows that GE 2.0 platform can capture 4.5 GWh energy in a year which is an acceptable quantity for wind energy.

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**ABBREVIATIONS**

- NASA** : National Aeronautic Space Administration
- GE** : General Electricity
- RMSE** : Root Mean Square Error
- PNL** : Battelle-Pacific Northwest Laboratory

onshore wind turbines produce 7.3 GW [5]. The major Scottish Government target is to deliver 30% of her energy demand by 2020 from renewable sources of energy as well as meeting the emissions mitigation targets as set under the Scotland Climate Change Act 2009. Producing wind energy has a vital role in meeting this target.

**1. INTRODUCTION**

The world experience shortage of conventional energy resources. The concern about the depletion of fossil fuels reservoirs and global warming drives countries into strong demand for an alternative source of energy especially the renewable sources of energy [1]. There are several renewable energy sources but wind energy is among the fastest growing energy generation technology which is highly preferred alternative to conventional energy sources. This is because wind energy is a clean renewable source of energy without direct gaseous emission into the environment [2,3,4]. The remarkable renewable energy deployment targets in the UK by 2020, the Scottish Government has targeted to produce 100% of her electricity from renewable sources of energy. This corresponds to approximated installed renewable capacity of 14-16 GW [5]. Currently,

Wind energy utilization depends on average wind speed and wind speed variation. Several techniques to identify the most potential wind sites are available in the literature [6].

In this paper, the standard deviation method has been utilized to determine the value of Weibull parameters [7,8] which are vital in assessing the wind energy potential of a site for power production.

**2. METHODOLOGY**

**2.1 Site Location**

Great Cumbrae Island lies on the coast of Ayrshire and is rough measures 11.5 square km. The geographical coordinates and the ground height from mean sea level of the Island are shown in Table 1.

**Table 1. Geographical location of Great Cumbrae Island**

Location	Height (m)	Longitude (°W)	Latitude (°N)
Great Cumbrae Island	65	4.92	55.75

**2.2 The Weibull Density Function**

The probability density function is given by several authors [8,9,10,11].

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

where **v** denotes wind velocity, **c** and **k** represent the Weibull scale and shape parameter respectively. This function illustrates the probability during which a particular wind speed dominates at a given site with the scale parameter indicating how ‘windy’ the site is [12].

Integrating probability density function gives cumulative density function, F (v, k, c), which is expressed as [8]:

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

Several methods have been proposed to determine Weibull parameters. Moment method (MM) is considered to be the most efficient in estimating Weibull parameters [13]. In this study, the standard deviation method (SDM) was used to determine the accuracy of the moment method. The standard deviation method is expressed as [14,15];

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

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

and the moment method expressed as [16];

$$k = \left(\frac{0.9874}{\sigma/v_m}\right)^{1.0983} \quad (5)$$

$$c = \frac{v_m}{\Gamma\left(1 + \frac{1}{k}\right)} \quad (6)$$

where  $\sigma$  stands for the determine wind speed standard deviation. Defined mathematically as:

$$\sigma = \left[\frac{1}{n-1} \sum_{i=1}^n (v_i - v_m)^2\right]^{0.5} \quad (7)$$

and mean wind speed  $v_m$  expressed as:

$$v_m = \frac{1}{n} \sum_{i=1}^n v_i \quad (8)$$

where  $v_i$  stands for the speed of the wind at time  $i$  and  $n$  denotes the sum of data set. The standard deviation indicates wind speed variation from the mean with low value implying that the wind velocity approaches the mean value. Furthermore, this indicates a high probability of producing a larger amount of power.

### 2.3 Wind Power Density

The power density of wind flowing through a wind turbine blade of sweep area  $A$  at speed  $v$  increases with the cube of wind speed. Compared to wind speed, the power density of wind is a more reliable parameter in estimating wind power potential of a site. It is expressed as [17]:

$$P(v) = \frac{1}{2} \rho A v^3 \quad (9)$$

Where  $\rho$  represent air density.

The Weibull density function ( $P_d$ ) is expressed as [11]:

$$P_d = \frac{1}{2} \rho c^3 \Gamma\left(1 + \frac{3}{k}\right) \quad (10)$$

For  $k = 2$ , the Weibull density function (equation 10) becomes Rayleigh density function as follow [14].

$$P_d = \frac{3}{\pi} \rho v_m^3 \quad (11)$$

### 2.4 The Most Frequent Wind Speed

This is the most possible wind speed a given site can experience [14,17]. In a probability distribution function, it is denoted by the peak of the distribution. It is given by:

$$v_{mp} = c \left(1 - \frac{1}{k}\right)^{\frac{1}{k}} \quad (12)$$

### 2.5 Optimal Wind Speed

This represents wind speed that generates the optimum amount of energy using a wind turbine [14,15]. It is mathematically stated as:

$$v_{op} = c \left(1 + \frac{2}{k}\right)^{\frac{1}{k}} \quad (13)$$

### 2.6 Annual Energy Production

The annual energy captured by a wind turbine given by:

$$E_{Annual} = 0.5 \rho c_p A v^3 \eta * 24 * 365 \quad (14)$$

### 2.7 Variation of Wind Speed with Height

Wind velocity varies as a power of height governed by the Hellmann exponential laws [18,19,20].

$$v = v_r \left(\frac{z}{10 m}\right)^\alpha \quad (15)$$

Where  $v$  stands for wind speed at tower height  $z$ ,  $v_r$  represent wind speed at 10 m height above ground level, while  $\alpha$  representing the Hellman coefficient which is 1/7 for our site [11]. At tower height (80 m) the wind speed was determined as follow:

$$v = 6.01 * \left(\frac{80}{10 m}\right)^{\frac{1}{7}} = 8.09 m/s \quad (16)$$

## 3. RESULTS AND DISCUSSION

### 3.1 Wind Speed Characteristics

Fig. 1 illustrates the Great Cumbrae Island monthly average wind speeds for the period 2008-2010 obtained from Met Office and a 10-year average wind speed from NASA. The analyses were done using OriginPro 8 software. In February 2010, the Island experienced the lowest monthly average wind speed of 4.0 ms<sup>-1</sup> and the highest 7.9 ms<sup>-1</sup> was experienced in March 2008. The Island received annual

average wind speeds of 6.08, 5.79 and 5.06  $\text{ms}^{-1}$  for 2008, 2009 and 2010 respectively with a 10-year average wind speed varying from 4.8  $\text{ms}^{-1}$  in July to 7.3  $\text{ms}^{-1}$  in January. Based on the rule of thumb for annual average wind speeds [16], Great Cumbrae Island is suitable for grid connected wind farm for power production.

### 3.2 Great Cumbrae Island Weibull Parameters

Fig. 2 shows the Weibull probability function spreading over a wider range. This distribution shows that Great Cumbrae Island mostly experiences wind speed higher than 5.0  $\text{ms}^{-1}$ .

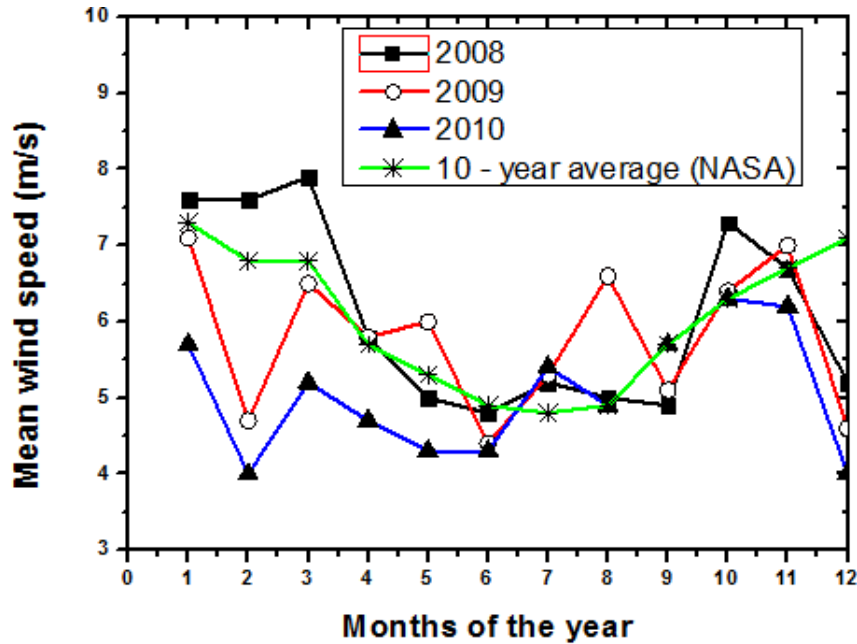


Fig. 1. Monthly average wind speed at 10 m elevation for Great Cumbrae Island

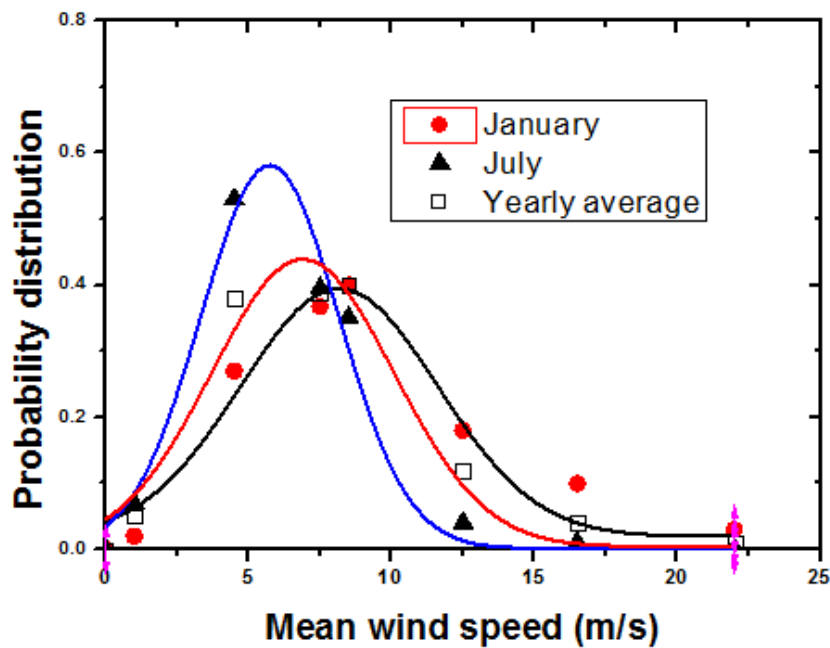


Fig. 2. The Weibull probability function

Fig. 3 shows a high probability (0.55) of the Island to experience annual average wind speed of more than 5.0  $ms^{-1}$ .

### 3.3 Weibull Parameters and Power Density Analysis

Table 2 shows the monthly wind speed characteristics of Great Cumbrae Island. The Weibull parameters were determined using equations (3-6). Based on Weibull distribution, equation (10) was used to determine the wind power density.

The parameter  $k$  and  $c$ , ranged from 2.102-2.495 and 10.383-6.556 m/s, respectively in different months of the year. The high values of  $c$  imply high values of  $v_m$  and the wide range distribution of the probability function. The Island experienced wind with the highest power density of 834.252  $W/m^2$  in January and the lowest power density of 211.797  $W/m^2$  in July. According to PNL wind power classification [21] shown in Table 4, the monthly average wind power density of Great Cumbrae Island mostly falls into class 4.

To test the accuracy of moment method with regard to the standard deviation method, the root means square error (RMSE) was used. This error is mathematically expressed as [22,23]:

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (y_i - x_i)^2}{N}} \quad (17)$$

Where  $y_i$  denotes the Weibull parameter value established using moment method,  $x_i$  represent the Weibull parameter value determined by the standard deviation method and  $N$  is the sum of data points.

The result of the statistical error analysis illustrated in Table 3 shows that the Moment Method is an accurate method because it has a small RMSE.

### 3.4 Wind Turbine Selection and Annual Energy Production

In this section, the production of four horizontal wind turbine models were calculated. Table 5 illustrates the characteristic of each model. The models were selected based on their tower height.

The annual power output captured by each wind turbine model was calculated using equation (11-13) With an efficiency of 50% ( $\eta$ ) and capacity factor 30% ( $c_p$ ) [25].

Fig. 4 shows the annual energy captured by each turbine model at a tower height of 80 m. GE 2.0 platform captured the highest energy and for this reason it is an ideal turbine model for the Island. About 4.5 GWh energy can be obtained in a year which is an acceptable quantity for wind energy. With the installation of a wind farm at the Island, more energy can be generated.

**Table 2. Wind speed characteristics for Great Cumbrae Island**

Months	$v_m$	$\sigma$	SDM		MM		$v_{op}$	$v_{mp}$	$P_d$
			$c$	$k$	$c$	$k$			
Jan	9.195	4.462	10.383	2.193	10.383	2.182	13.954	7.866	834.252
Feb	8.551	4.292	9.655	2.114	9.655	2.102	13.229	7.131	693.380
Mar	8.688	3.934	9.805	2.364	9.804	2.354	12.708	7.770	661.375
Apr	7.106	3.052	8.012	2.504	8.009	2.495	10.128	6.536	346.704
May	6.690	3.025	7.550	2.368	7.549	2.358	9.778	5.988	301.607
Jun	6.135	2.656	6.918	2.482	6.916	2.473	8.778	5.620	224.538
Jul	5.990	2.638	6.757	2.437	6.556	2.427	8.640	5.440	211.797
Aug	6.215	2.898	7.017	2.290	7.016	2.280	9.230	5.461	248.395
Sep	7.285	3.396	8.225	2.291	8.224	2.280	10.816	6.403	398.911
Oct	8.055	3.881	9.096	2.210	9.095	2.199	12.176	6.926	557.173
Nov	8.290	3.870	9.360	2.287	9.359	2.277	12.319	7.279	590.182
Dec	8.980	4.087	10.136	2.351	10.134	2.341	13.169	8.008	733.685
Average	7.598	3.516	8.576	2.324	8.558	2.314	11.244	6.702	483.500

**Table 3. Statistical error analysis summary**

Weibull parameter	Statistical methods		Statistical test
	MM	SDM	RMSE
$k$	2.314	2.324	0.0355
$c$ ( $ms^{-1}$ )	8.558	8.576	0.0618

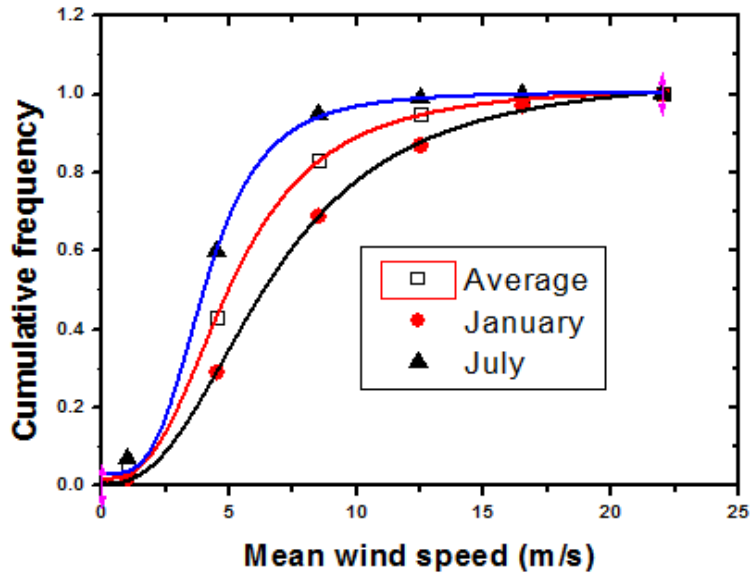


Fig. 3. The Weibull frequency distribution

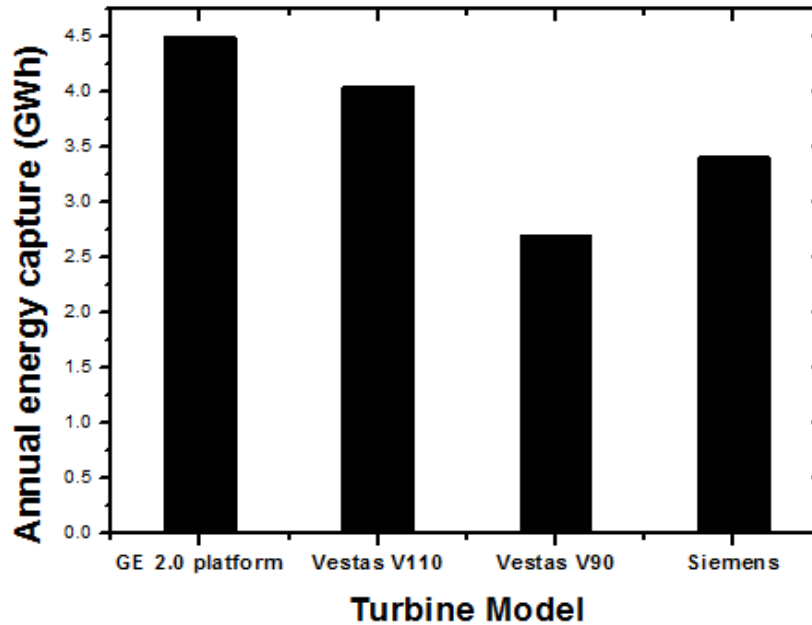


Fig. 4. Annual energy produced from wind turbines at tower height 80 m

Table 4. PNL wind power classification for 50 m elevation [24]

Wind power class	Potential	Wind speed (m/s)	Wind Power ( $W/m^2$ )
1	Poor	$0.0 < v \leq 5.6$	$0 < P_d \leq 200$
2	Marginal	$5.6 < v \leq 6.4$	$200 < P_d \leq 300$
3	Moderate	$6.4 < v \leq 7.0$	$300 < P_d \leq 400$
4	Good	$7.0 < v \leq 7.5$	$400 < P_d \leq 500$
5	Excellent	$7.5 < v \leq 8.0$	$500 < P_d \leq 600$
6	Excellent	$8.0 < v \leq 8.8$	$600 < P_d \leq 800$
7	Excellent	More than 8.8	More than 800

**Table 5. Characteristic wind turbine [26,27,28,29]**

Model	Rated Power (kW)	Tower height (m)	Rotor diameter (m)
V110-Vestas	2,000	80	110
V90-Vestas	2,000	80	90
GE 2.0 platform	2,000	80	116
Siemens	2,300	80	101

**4. CONCLUSION**

The following is the summary of the most crucial findings of this study:

1. The annual Weibull shape parameter values at 50 m elevation ranged between 2.102 and 2.495 with an average value of 2.314 see Table 2. This value indicates a site with a slight hourly mean wind speed variation about the yearly wind speed resulting in a good quality wind power production.
2. Great Cumbrae Island mostly experiences annual average wind speed of more than 5.0  $ms^{-1}$ . This makes the Island suitable for grid connected wind farm for power production.
3. From the assessment conducted it was found that Great Cumbrae Island receives wind of power density of 483.50  $W/m^2$ . According to PNL wind power classification, Great Cumbrae Island falls into class 4. It is therefore a suitable site for installation of the wind farm for power production.
4. The calculated annual energy captured by four wind turbines model shows a high probability of generating higher than 4.5 GWh energy with the installation of a wind farm at the Island.

**COMPETING INTERESTS**

Authors have declared that no competing interests exist.

**REFERENCES**

1. Rokni M. Thermodynamics analyses of municipal solid waste gasification plant integrated with solid oxide fuel cell and stirling hybrid system. *International Journal of Hydrogen Energy*. 2015;40:7855-69.
2. Og̃ulata RT. Energy sector and wind energy potential in Turkey. *Renewable and Sustainable Energy Reviews*. 2003;7:469–84.
3. U.S. Department of Energy. Energy efficiency and renewable energy:

Strengthening America’s energy security with offshore wind; 2012. (Accessed on 07 November 2018) Available:<http://www.nrel.gov/docs/fy12osti/49222.pdf>

4. Evans A, Strezov V, Evans TM. Assessment of sustainability indicators for renewable energy technologies. *Renewable and Sustainable Energy Review*. 2009;13:1082–88.
5. Department of Energy and Climate Change. Delivering United Kingdom Energy Investment; 2014. (Accessed on 25 June 2018) Available:[https://assets.publishing.service.gov.uk/.../DECC\\_Energy\\_Investment\\_Report.pdf](https://assets.publishing.service.gov.uk/.../DECC_Energy_Investment_Report.pdf)
6. Chang TP. Performance comparison of six numerical methods in estimating weibull parameters for wind energy application. *Applied Energy*. 2011;88:272-82.
7. Lun IY, Lam JC. A study of weibull parameters using long-term wind observations. *Renewable Energy*. 2000;20:145-53.
8. Chang TP. Estimation of wind energy potential using different probability density functions. *Applied Energy*. 2011;88:1848-56.
9. Piotr W. A review of weibull functions in wind sector. *Renewable and Sustainable Energy Reviews*. 2017;70:1099-1107.
10. Fadare DA. A statistical analysis of wind energy potential in Ibadan, Nigeria, based on weibull distribution function. *Pac J Sci Technol*. 2008;9(1):110-19.
11. Akpınar EK, Akpınar S. An assessment on seasonal analysis of wind energy characteristics and wind turbine characteristics. *Energy Conversion Management*. 2005;46:515-32.
12. Shonhiwa C, Mukumba P. An assessment of wind power generation potential for Margate town in South Africa. *International Journal of Energy and Power Engineering*. 2015;4(2):32-37.
13. Azad A, Rasul M, Yusaf T. Statistical diagnosis of the best weibull methods for wind power assessment for agricultural applications. *Energies*. 2014;7:3056-85.

14. Adaramola MS, Agelin-chaab M, Paul SS. Assessment of wind power generation along the coast of Ghana. *Energy Conversion Management*. 2014;77:61-69.
15. Azad AK, Rasul MG, Islam R, Shishir IR. Analysis of wind energy prospect for power generation by three weibull distribution methods. *The 7<sup>th</sup> International Conference on Applied Energy*. 2015;75:722-27.
16. Aukitino T, Khan MGM, Ahmed RM. Wind energy resource assessment for Kiribati with a comparison of different methods of determining weibull parameters. *Energy Conversion and Management*. 2017;151: 641-60.
17. Ayodele TR, Jimoh AA, Munda JL, Agee JT. Statistical analysis of wind speed and wind power potential of Port Elizabeth using weibull parameters. *Journal of Energy in Southern Africa*. 2012;23-30.
18. Di Piazza A, Di Piazza MC, Ragusa A, Vitale G. Statistical processing of wind speed data for energy forecast and planning. *International Conference on Renewable Energies and Power Quality*. Granada, Spain; 2010.
19. Saeidi D, Mirhosseini M, Sedaghat A, Mostafaeipour A. Feasibility study of wind wind energy potential in two provinces of Iran: North and South Khorasan. *Renewable Sustainable Energy Review*. 2011;15(8):3558-69.
20. Bañuelos-Ruedas F, Angeles-Camacho C, Rios-Marcuella S. Analysis and validation of the methodology used in the extrapolation of wind speed data at different heights. *Renewable and Sustainable Energy Review*. 2010;14: 2383-91.
21. American Wind Energy Association. Basic principles of wind resource evaluation; 1998. (Accessed 01 July 2018)
22. Ozay C, Celik MS. Statistical analysis of wind speed using two-parameter weibull distribution in Alaçati region. *Energy Conversion and Management*. 2016;121: 49-54.
23. Indhumathy D, Seshaiyah CV, Sukkiramathi K. Estimation of weibull parameters for wind speed calculation at Kanyakumari India. *International Journal of Innovative Research in Science, Engineering and Technology*. 2014;3(1):8340-45.
24. Mostafaeipour A, Sedaghat A, Dehghan-Niri AA, Kalantar V. Wind energy feasibility study for city of Shahrabak in Iran. *Renewable and Sustainable Energy Reviews*. 2011;15:2545-56.
25. MacKay DJC. *Sustainable Energy – without the hot air*. England: UIT Cambridge; 2008.
26. AWE0.org. Size specifications of common industrial wind turbines. (Accessed on 12 November 2018) Available:<http://www.aweo.org/windmodels.html>
27. Windustry. Turbine selection and purchase. (Accessed on 10 November 2018) Available:[http://www.windustry.org/community\\_wind\\_toolbox\\_15\\_turbine\\_selection\\_and\\_purchase](http://www.windustry.org/community_wind_toolbox_15_turbine_selection_and_purchase)
28. Windpower. Ten of the biggest and the best manufacturers. (Accessed on 10 November 2018) Available:<http://www.windpowermonthly.com/article/1352888>
29. Wind Energy Market Intelligence. Manufacturers and turbines. (Accessed on 12 November 2018) Available:[http://www.thewindpower.net/turbine\\_en\\_34\\_vestas\\_2750.php](http://www.thewindpower.net/turbine_en_34_vestas_2750.php)

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