Open Access Journal

Journal of Power Technologies 95 (1) (2015) 48–53

journal homepage:papers.itc.pw.edu.pl

Evaluation of Wind Energy Potential for Four Sites in Ireland using the Weibull Distribution Model

Parikshit Gautam Jamdade[a*], Shrinivas Gautamrao Jamdade[b]

[a]*Department of Electrical Engineering, PVG's College of Engineering and Technology, Pune, Maharashtra, India*

[b]*Department of Physics, Nowrosjee Wadia College, Pune, Maharashtra, India*

Abstract

Wind speed is receiving greater attention in the design and study of wind energy conversion systems (WECS). Using meteorological data, this paper studies the availability of wind energy potential at four sites in Ireland: Malin Head, Dublin Airport, Belmullet and Mullingar. An analysis is made of mean wind speed data collected at a height of 50 m above ground level at each site over a period of seven years. A two parameter Weibull distribution model is used to analyze wind speed pattern variations. Weibull parameters are calculated by the Least Squares Method (LSM). The results relating to wind energy potential are given in terms of the density function. Analysis shows that coastal sites of Ireland such as Malin Head, Dublin Airport and Belmullet have good wind power potential.

Keywords: Wind Energy Conversion Systems (WECS), Wind Power Potential (WPP), Weibull Distribution Model (WDM), Cumulative Density Function (CDF), Least Squares Fit Method (LSM)

1. Introduction

Burning of fossil fuel to satisfy energy demand is causing huge environmental problems. Some of major environmental problems are increasing in aridity level, flooding in some regions and droughts in others, acid rain, sea level rising and greenhouse effects etc. Out of concerns over climate change there is a move toward renewable and sustainable energy sources to satisfy energy demand [1, 2]. Wind energy is an important clean energy source and one which is freely available. When contemplating a wind energy project a wind resource assessment is the most crucial step. The assessment will form the basis for a feasibility study to:

- Analyze the comparative economic and financial viability of the project and propose a decision for implementation, setting out related benefits for the economic development and welfare of the region. The costs include investment, operation and maintenance and development
- Identify specific environmental constraints on the project layout [3]
- Identify possible planning constraints [4]
- Evaluate additional investment costs for the tower and foundation [4]
- Design the technical layout of the site [5, 6]
- Evaluate different operation models
- Decide on wind turbine type and capacity [7, 8]
- Choose suitable tower heights considering the local wind profile. Higher towers can harness higher wind speeds, thereby increasing energy production correspondingly [9–11]

In the design and study of wind energy conversion systems (WECS) wind speed is the most important parameter. Wind speed varies with time of day, season, height

*Corresponding author

Email address: parikshit_jamdade@yahoo.co.in (Parikshit Gautam Jamdade[a*])

above ground, type of terrain and global location. Topology and built structures are also important for determining wind resource. High surface roughness and larger obstacles in the path of the wind result in turbulence and lower wind speed. Accurate information about wind speed is very important when assessing the wind power potential (WPP) of a site. One way forward—used in this research—is to describe the wind using probability methods [12–17]. The paper is organized as follows:

Section 2 brief information on Ireland,

Section 3 information on the chosen sites and the data set used in this study,

Section 4 estimation of wind power potential, Section 5 - wind characteristics and analytical model,

Section 6 results and discussion,

Section 7 conclusion.

2. Description of Ireland

Ireland is a country with increasing energy demand. In terms of GDP per capita, Ireland is one of the wealthiest countries in the European Union. Ireland, which has a prevailing westerly wind from the Atlantic Ocean, has extensive coastal areas for wind farm developments. There is considerable potential for wind farms in urban environments and rural locations alike, although farmland, and especially developed and semi-developed grass lands for livestock, provides ideal locations for harnessing wind energy due to their lower surface roughness. Ireland rarely experiences extreme weather events and has low variations in temperatures. The geographic location of Ireland means it has almost daily wind with reasonable duration and magnitude. According to the European wind atlas Ireland is one of the windiest regions in Europe at 50 m above ground level, but it harnesses comparatively little of its wind energy potential in European terms. Therefore it is necessary to carry out a study of the wind resources available in Ireland.

3. Data Source

In general, hourly wind speed indicates the average value of wind speed during a given hour. Evidently, the wind speed varies during that hour and this may result in some error. One way to minimize error is to calculate the wind power potential by using the monthly average value of wind speed, which is what we do in this study.

Figure 1: The four chosen locations on a map of Ireland

Table 1: Coordinates of the four chosen locations in Ireland

Name	Latitude N°	Longitude W°
Malin Head Co. Donegal	55°23'N	07°23'W
Dublin Airport Co. Dublin	53°21'N	06°15'W
Belmullet Co. Mayo	54°14'N	09°58'W
Mullingar Co. Westmeath	53°31'N	07°21'W

The meteorological office supplied the data set for the period 2007...2011, containing the mean wind speed of each month in Ireland with an observation height of 50 m above ground level. The four chosen locations in Ireland are given in Table 1 and shown on the map in Fig. 1.

4. Estimation of Wind Power Potential

If "m" is the mass of the air and "V" is the wind speed, then the kinetic energy (KE) available in the wind can be written as

$$KE = \frac{1}{2} \cdot m \cdot V^2 \quad (1)$$

If "ρ" is the air density and "v" is the volume of air, then mass of air can be given as $m = \rho \cdot v$. Using above equations KE will be

$$KE = \frac{1}{2} \cdot \rho \cdot v \cdot V^2 \qquad (2)$$

The volume of air means the volume of an air parcel available for the rotor. If the air parcel interacts with the turbine through a rotor having a turbine blade of cross-sectional area "A", then the total volume of wind passing through the turbine is $v = A \cdot V$. Hence, the power available in the wind stream can be given as

$$P = \frac{1}{2} \cdot \rho \cdot A \cdot V^3 \qquad (3)$$

Thus, wind is a movement of air having kinetic energy. This kinetic energy is converted into electrical energy with the help of a wind turbine.

P is power in kW, ρ is air density, which is taken as 1.225 kg/m^3 of average atmospheric pressure at sea level and at 15°C temperature, which depends in turn on altitude, air pressure and temperature, A is the rotor swept area in m^2.

Swept Rotor Area= $A = \pi \times r^2$ where r is the rotor radius and V is the wind speed in m/s.

This shows that available wind power is directly proportional to the cube of wind speed. Therefore a small change in wind speed can have substantial changes in the wind energy resource. Wind speed also affects wind turbine design, playing a key role in the calculation of wind turbine loading, for example turbulence intensity, wind shear across the turbine blades, and transient wind conditions such as extreme wind speeds and directional changes [2]. As wind speed is a random phenomenon, wind speed alone does not enable us to accurately predict the wind power potential (WPP) of a given site. For a more accurate assessment of WPP, we use probability methods.

5. Wind Characteristics and Analytical Model

Insightful statistical analysis of wind speed data is a vital part of any wind resource assessment. Assessment of the wind power potential needs to be as accurate as possible and take into account yearly as well as seasonal changes in the wind resource. Probability distribution is an approach which indicates the probability of each data point in the data set. The probability density function (PDF) and cumulative density function (CDF) of wind speeds are vital in many wind energy applications. Much valuable work has been done by many authors—through the use of several probability distributions—to describe wind speed variations. The Rayleigh model is actually used for constant variation in variable quantity, the normal model is used for consistent variation pattern in variable quantity while the extreme value distribution model is used for extreme variation in variable quantity. Wind speed variation is random in nature so the results given by these models are inaccurate. In the case of the Weibull model the parameters depend on actual variation in variable quantity, as compared to the other models, therefore the Weibull model is widely accepted and used in the wind energy industry as the preferred method for describing wind speed variations at a given site [18–24]. In this paper two parameter Weibull Distribution is used for describing wind pattern variations if wind variations follow the Weibull probability density function.

The probability distribution is given as

$$\mathrm{F}(\mathrm{V_i}) = \int_0^\infty f(\mathrm{V_i})\mathrm{dV}$$

The Probability Density Function (PDF) of Weibull distribution is

$$f(\mathrm{V_i}) = \frac{\mathrm{k}}{\mathrm{c}}\left(\frac{\mathrm{V_i}}{\mathrm{c}}\right)^{\mathrm{k}-1} \exp\left[-\left(\frac{\mathrm{V_i}}{c}\right)^{\mathrm{k}}\right] \qquad (4)$$

The area under this curve is equal to unity.

The Cumulative Density Function (CDF) of Weibull distribution is

$$\mathrm{F}(\mathrm{V_i}) = 1 - \exp\left[-\left(\frac{\mathrm{V_i}}{\mathrm{c}}\right)^{\mathrm{k}}\right] \qquad (5)$$

Where c is a scale parameter and k is the dimensionless shape parameter.

Cumulative Density Function (CDF) indicates the fraction of time for which the wind is at a given velocity. It can be calculated by accumulating the probability of wind speed as it increases from low to high.

There are several methods available for determining the Weibull parameters c and k but for calculation purpose the Least Squares Method (LSM) is used. Weibull parameters were estimated numerically for four sites as shown in Table 2.

6. Results and Discussions

To create the wind speed distribution for analysis of the wind power potential of the four locations, the Weibull distributions CDF plot for each of five years were plotted and analyzed. Figs 2...5 show the wind speed variation patterns in terms of cumulative density function

Table 2: Annual Weibull Parameters of Wind Speed estimated for four sites in Ireland

Year	Malin Head		Dublin Airport		Belmullet		Mullingar	
	c	k	c	k	c	k	c	k
2007	30.8	4.6	22.9	5.2	24.3	3.4	13.7	4.9
2008	33.7	5.8	24.1	6.1	25.1	5.4	13.7	5.2
2009	27.8	6.8	22.7	7.4	24.2	6.9	12.6	6.4
2010	27.4	4.6	19.3	7.7	20.7	5.7	10.8	6.3
2011	32.8	3.5	23.8	4.2	25.9	4.1	13.7	3.6

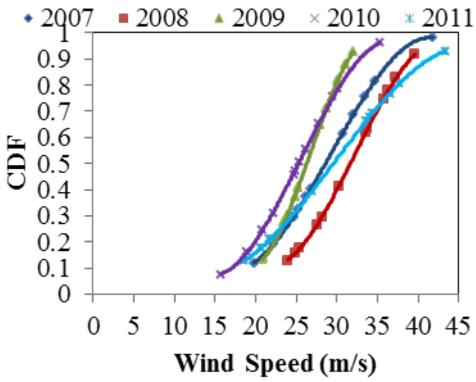

Figure 2: Variations in CDF of Wind Speed for Malin Head location.

(CDF) values wind speed for Malin Head, Dublin Airport, Belmullet and Mullingar respectively. To determine the Weibull cumulative distribution function, it is necessary to determine first the scale parameter (c) and shape parameter (k). Table 2 shows the annual Weibull distribution parameters of wind speeds estimated for four sites in Ireland. The scale parameter represents the variation in the value of wind speed while the shape parameter represents the deviation in wind speed from mean value of wind speed. Scale parameter (c) varies between 33.75 to 27.43 m/s, 24.15 to 19.32 m/s, 25.97 to 20.73 m/s and

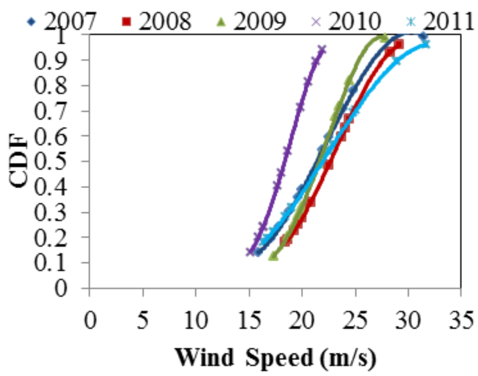

Figure 3: Variations in CDF of Wind Speed for Dublin Airport location.

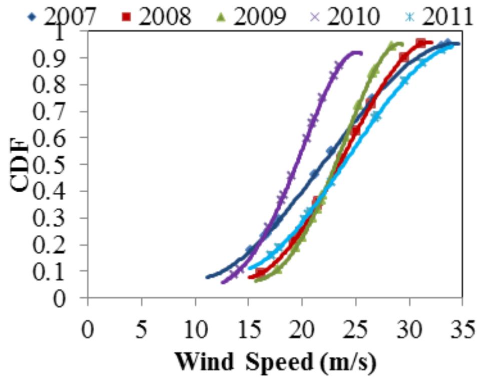

Figure 4: Variations in CDF of Wind Speed for Belmullet location.

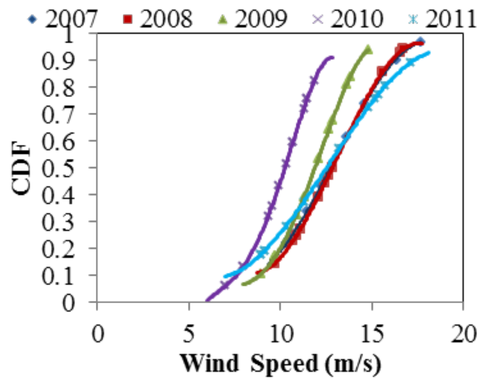

Figure 5: Variations in CDF of Wind Speed for Mullingar location.

13.72 to 10.79 m/s for Malin Head, Dublin Airport, Belmullet and Mullingar respectively. Shape parameter (k) varies between 6.82 to 3.47, 7.71 to 4.18, 6.88 to 3.38 and 6.38 to 3.62 for Malin Head, Dublin Airport, Belmullet and Mullingar respectively. It is clear that the scale parameter (c) has smaller variations in magnitude than the shape parameter (k).

In the case of Malin Head, the shape parameter is large in 2008 while the scale parameter is large in 2009, which shows that wind power production is large in 2008 but wind speed fluctuation is large in 2009. The shape parameter is lower in 2010 while the scale parameter is lower in 2011, indicating that wind power production is low in 2010, but wind speed fluctuation is low in 2011. In the case of Dublin Airport, the shape parameter is large in 2008 while scale parameter is large in 2010, which shows that wind power production is large in 2008, but wind speed fluctuation is large in 2010. The shape parameter is lower in the 2010 while the scale parameter is lower in 2011, indicating that wind power production is low in 2010, but wind speed fluctuation is low in 2011.

In the case of Belmullet, the shape parameter is large in 2011 while the scale parameter is large in 2009, which shows that wind power production is large in 2011, but wind speed fluctuation is large in 2009.

The shape parameter is lower in 2010 while the scale parameter is lower in 2007, indicating that wind power production is low in 2010, but wind speed fluctuation is low in 2007. In the case of Mullingar, the shape parameter is large in 2011 while scale parameter is large in 2009, which shows that wind power production is large in 2011, but wind speed fluctuation is large in 2009. The shape parameter is lower in 2010 while scale parameter is lower in 2011, indicating that wind power production is low in 2010, but wind speed fluctuation is low in 2011. Summarizing this, in 2010, wind power production is large in all locations while there is less variation in wind speed in 2011.

This indicates that the north and the west costal sites of Ireland have a more variable and gusty wind flow pattern compared to the east coastal sites, as they have high values of the c and k parameters. Locations in inland Ireland have a low speed magnitude of wind with smooth wind flow patterns throughout the study period, as the c and k parameters have low values.

In the case of the Malin Head site the CDF plot has a large magnitude in 2008 compared to other years and the CDF plots are located to the left side of the CDF plot of 2008. This indicates that the magnitude of wind speed is large in 2008. For the Dublin Airport site, for 2010, the CDF plot lies on the extreme left side of other years' CDFs. This means that lower values of wind speed occur in 2010 compared to other years, which reduce the wind power production in 2010. For the Belmullet site, the CDF plots of all years are located in a wind speed range of 21 m/s to 36 m/s except in 2010. So wind power production is almost constant throughout the years. For the Mullingar site, the CDF plots are plotted in a wind speed range of 6.4 m/s to 17.6 m/s and are always low compared to other sites.

So wind power production is lower compared to other sites. Hence, the Mullingar site is the least suitable of the four sites for setting up a wind farm.

In the case of Malin Head during the study period there was a 20% probability of getting wind speed in the range 29 to 37 m/s, a 50% probability of getting wind speed in the range 25 to 28.5 m/s, and a 70% probability of getting wind speed in the range 21 to 28.5 m/s. In the case of Dublin Airport during the study period there was a 20% probability of getting wind speed in the range 20.5 to 28.5 m/s, a 50% probability of getting wind speed in the range 18.5 to 23.5 m/s, and a 70% probability of getting wind speed in the range 16.5 to 20.5 m/s.

In the case of Belmullet during the study period there was a 20% probability of getting wind speed in the range 22.5 to 28.5 m/s, a 50% probability of getting wind speed in the range 18 to 24.5 m/s, and a 70% probability of getting wind speed in the range 17 to 20.5 m/s.

In the case of Mullingar during the study period there was a 20% probability of getting wind speed in the range 12.5 to 16.5 m/s, a 50% probability of getting wind speed in the range 10.5 to 13.5 m/s, and a 70% probability of getting wind speed in the range 8 to 11.5 m/s.

From Table 2 we can summarize that a higher value of the scale parameter combined with a lower value of the shape parameter results in high wind power production and provides a constant power supply resource. Existing data resources and CDF variation patterns indicate that of the locations studied Malin Head is the most suitable location for wind power development, Belmullet is the second most suitable site for wind farm development while Mullingar is the least suitable location.

7. Conclusion

This paper presents an assessment of the wind power potential of four locations in Ireland for the purpose of identifying wind farm sites. A two parameter Weibull distribution model is used to model wind speed variations. Weibull distribution parameters are calculated using the Least Squares Method (LSM). Existing data research and CDF variation patterns indicate that of the locations studied Malin Head is the most suitable location for wind power development and Belmullet is the second most suitable site for wind farm development while Mullingar is the least suitable location. On average, there is a 70% probability of getting wind speed of 24.5, 18.5, 18 and 10.5 m/s in the case of the Malin Head, Dublin Airport, Belmullet and Mullingar locations respectively. This informs the choice of wind turbine so as to maximize the power can be extracted.

References

[1] M. Tingem, M. Rivington, S. A. Ali, J. Colls, Assessment of the climgen stochastic weather generator at cameroon sites, African Journal of Environmental Science and Technology 1 (4) (2007) 86 – 92.

[2] S. C. Pryor, R. J. Barthelmie, Climate change impacts on wind energy: a review, Renewable and Sustainable Energy Reviews 14 (2010) 430 – 437.

[3] V. Akhmatov, Influence of wind direction on intense power fluctuations in large offshore wind farms in the north sea, Wind Eng. 3 (1) (2007) 59 –64.

[4] R. C. Bansal, A. F. Zobaa, R. K. Saket, Some issues related to power generation using wind energy conversion systems: An overview, International Journal Emerging Electrical Power System 3 (2) (2005) 1 – 19.

[5] C. Wan, Z. Xu, P. Pinson, Z. Y. Dong, K. P. Wong, Probabilistic forecasting of wind power generation using extreme learning machine, IEEE Transactions on Power Systems 29 (3) (2014) 1033 – 1044.

[6] S. M. Weekes, A. S. Tomlin, Low-cost wind resource assessment for small-scale turbine installations using site pre-screening and short-term wind measurements, Renewable Power Generation, IET 8 (4) (2014) 348–358.

[7] T. J. Chang, Y. L. Tu, Evaluation of monthly capacity factor of wecs using chronological and probabilistic wind speed data: A case study of taiwan, Renewable Energy 32 (2) (2007) 1999 – 2010.

[8] S. J. Huang, H. H. Wan, Enhancement of matching turbine generators with wind regime using capacity factor curves stratergies, IEEE Transaction Energy Conversion 24 (2) (2009) 551 – 553.

[9] J. W. Taylor, P. E. McSharry, R. Buizza, Wind power density forecasting using ensemble predictions and time series models, IEEE Trans. Energy Convers. 24 (3) (2009) 775 –782.

[10] A. Khosravi, S. Nahavandi, D. Creighton, Prediction intervals for short-term wind farm power generation forecasts, IEEE Trans. Sustain. Energy 24 (3) (2013) 602 –610.

[11] R. D. Prasad, R. C. Bansal, M. Sauturaga, Wind energy analysis for vadravadra site in fiji islands: A case study, IEEE Transaction Energy Conversion 24 (3) (24) 1537 – 1543.

[12] J. A. Carta, P. Ramiez, Influence of the data sampling interval in the estimation of the parameters of the weibull wind speed probability density distribution: a case study, Energy Conversion Management 46 (15) (2005) 2419 – 2438.

[13] M. A. Matos, R. J. Bessa, Setting the operating reserve usi1ng probabilistic wind power forecasts, IEEE Trans. Power Syst. 26 (2) (2011) 594 –603.

[14] R. J. Bessa, V. Miranda, A. Botterud, Z. Zhou, J. Wang, Time-adaptive quantile copula for wind power probabilistic forecasting, Renew. Energy 40 (1) (2012) 29 –39.

[15] G. Sideratos, N. D. Hatziargyriou, Probabilistic wind power forecasting using radial basis function neural networks, IEEE Trans. Power Syst. 27 (4) (2012) 1788 –1796.

[16] H. Bludszuweit, J. A. Dominguez-Navarro, A. Llombart, Statistical analysis of wind power forecast error, IEEE Trans. Power Syst. 23 (3) (2008) 983 –991.

[17] K. Bhaskar, S. N. Singh, Awnn-assisted wind power forecasting using feed-forward neural network, IEEE Trans. Sustain. Energy 3 (2) (2012) 306 –315.

[18] A. N. Celick, A statistical analysis of wind density based on the weibull and rayleigh models at the southern region of turkey, Energy Conversion Management 29 (4) (2004) 593 – 604.

[19] S. G. Jamdade, P. G. Jamdade, Extreme value distribution model for analysis of wind speed data for four locations in ireland, International Journal of Advanced Renewable Energy Research 1 (5) (2012) 254 – 259.

[20] S. G. Jamdade, P. G. Jamdade, Analysis of wind speed data for four locations in ireland based on weibull distribution's linear regression model, International Journal of Renewable Energy Research 2 (3) (2012) 451 – 455.

[21] R. J. Bessa, V. Miranda, A. Botterud, J. Wang, E. M. Constantinescu, Time adaptive conditional kernel density estimation for wind power forecasting, IEEE Trans. Sustain. Energy 3 (4) (2012) 660 –669.

[22] A. M. Foley, P. Leahy, A. Marvuglia, E. J. McKeogh, Current methods and advances in forecasting of wind power generation, Renewable Energy 37 (1) (2012) 1–8.

[23] P. Pinson, G. Kariniotakis, Conditional prediction intervals of wind power generation, IEEE Trans. Power Syst. 25 (4) (2012) 1845 –1856.

[24] A. Khosravi, S. Nahavandi, D. Creighton, Prediction intervals for short-term wind farm power generation forecasts, IEEE Trans. Sustain. Energy 4 (3) (2013) 602 –610.

Nomenclature

ρ Air density, kg/m^3

A Turbine blade of cross-sectional area, m^3

c Scale parameter, m/s

i Subscript referring to monthly mean wind speed

k Shape parameter

m Mass of the air, kg

P Power, kW

r Rotor radius, m

V Wind speed, m/s

v Volume of air, m^3

CDF cumulative density function ($F(V_i)$)

KE Kinetic energy, kW

PDF probability density function ($f(V_i)$)