Computers & Geosciences 71 (2014) 62–72

Contents lists available at ScienceDirect

Computers & Geosciences

journal homepage: www.elsevier.com/locate/cageo

A wind chart to characterize potential offshore wind energy sites

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ARTICLE INFO

Article history:
Received 2 August 2013
Received in revised form
24 December 2013
Accepted 17 January 2014
Available online 7 February 2014

Keywords:
Wind resource
Wind distribution
Wind energy
Matlab
Wind conditions
Marine wind

ABSTRACT

Offshore wind industry needs to improve wind assessment in order to decrease the uncertainty associated to wind resource and its influence on financial requirements. Here, several features related to offshore wind resource assessment are discussed, such as input wind data, estimation of long-term and extreme wind statistics, the wind profile and climate variations.

This work proposes an analytical method to characterize wind resource. Final product is a wind chart containing useful wind information that can be applied to any offshore sites. Using long-term time series of meteorological variables (e.g. wind speed and direction at different heights), the methodology is applied to five pilot sites in different countries along European Atlantic corridor and it is used to describe and compare offshore wind behavior.

1. Introduction

Offshore wind in Europe is concentrated in the North Sea and the Baltic Sea. This fact is due to the characteristics of these northern seas: a depth of no more than 60 m and continuous persistence of high marine winds. The wide area of low depth allows the foundation of turbines directly to seabed with monopiles or jackets and the favorable winds provide a simple wind energy potential. European future of offshore wind energy is based in the Atlantic corridor the Mediterranean Sea and the Black Sea, taking into account countries as Ireland, France or Spain.

These regions have completely different characteristics than northern European seas. In the Atlantic region, continental shelf has deep depths and wind farms must be sited far shore (more than 20 km) looking for great wind energy potential. These two characteristics are the main challenges offshore wind industry should face in the future. The other main challenge is the development of floating platforms technology. Their purpose is to be able to reach higher wind energy potential levels without increasing too much the investment.

The costs of an offshore wind farm are considerably higher than those of an onshore one and future locations will need greater investments. The best wind assessment is needed in terms of reducing the uncertainty of these investments.

The statistical analysis from long enough wind time series is the first step to do a viability assessment as a filter of different potential locations (Sempreviva et al., 2008). Several features are relevant to evaluate the viability of an offshore wind farm from the wind characteristics, such as the wind distribution (Morgan et al., 2011; Carta et al., 2009; Jaramillo and Borja, 2004), the extreme wind events (Duroñana et al., 2007), the wind variability thorough the time or the vertical wind profile.

Historically, the Weibull distribution has generally been accepted to represent the statistical structure of the wind speed probability density function, particularly over water surfaces (e.g. Pavia et al., 1986; Monahan, 2006). Extreme winds, associated to a specific return period (e.g. 50-yr wind return level)and wind speed at a particular height is usually required for design purposes. Long-term climate variations provides information about the possible changes on wind efficiency due to seasonality or larger time scales variations, however, a least one year of continuous monitoring of wind speed is used in practice to estimate wind characteristics.

The main goal of this paper is to develop an integrated methodology to characterize local wind resource by means of a wind chart. The methodology has been integrated in package coded in Matlab. The package has been applied over five locations along the European Atlantic corridor and the obtained wind charts provide useful information about the offshore wind.

The paper is arranged as follows. Some basic concepts about wind properties are explained in Section 2. In Section 3, the methodology is outlined, putting special emphasis on input data, wind distribution, wind profile and wind variability. In Section 4, some applications of the wind chart for five study sites are shown. Finally, some conclusions are provided.

2. Basic concepts

The characterization of wind resource entails several statistics commonly used for geophysical variables, such as directional

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http://dx.doi.org/10.1016/j.cageo.2014.01.008
0098-3004

description or basic climatologies. Two features are, however, of particular interest to evaluate offshore wind energy resource: wind distribution and wind profile. The former is important to understand the probability of occurrence of different wind speeds, providing statistics and extremes (maxima and minima values). The latter is obtained to understand the wind vertical variation from sea surface to the first atmospheric 200 m in order to evaluate the potential wind power at a specific hub height. The relationship between wind speed (u) and wind power (P) shows the importance of accurate wind speed assessment. Wind power is the time rate of change in kinetic energy (KE) due to air stream per unit area hence proportional to the third power of the wind speed.

$$P=\frac{dKE}{dt}=\frac{1}{2}\rho u^3 , \tag{1}$$

where ρ is the air density.

2.1. Wind distribution

In order to calculate wind power from a specific wind turbine design over a range of wind speed values, a generalized expression of the distribution is required for the probability density function (PDF). The Weibull distribution function has demonstrated to fit quite well to wind speed data (Fréchet, 1927; Rosin and Rammler, 1993), especially over water surfaces (Pavia et al., 1986; Menendez et al., 2013). The Weibull PDF with two parameters (k, λ), can be expressed as

$$f(x;\lambda,k)=\begin{cases}0, & x<0\\ \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1}e^{-(x/\lambda)^k}, & x\geq 0\end{cases} \tag{2}$$

where λ is the scale parameter which is related to the mean of the distribution and k is the dimensionless shape parameter and it describes the spread of the distribution. Rayleigh distribution can be used as a simpler model to characterize wind distribution if the value of the shape parameter k is approximately two.

Different estimators of Weibull parameters λ and k can be used (Monahan, 2006), such as (i) estimates obtained using sample estimates of mean($\ln x$) and std($\ln x$); (ii) maximum likelihood estimates and (iii) estimates from some approximations, using sample estimates of $mean(x)$ and $std(x)$. Negligible differences have been found on estimated parameters for large sample sizes (Pryor et al., 2004), therefore, in this case, the parameters are estimated by the maximum likelihood method.

A classical theorem in extreme value theory (Coles, 2001) states that the limit distribution of properly normalized maxima is the generalized extreme value (GEV) family of distributions. The GEV extreme distribution combines three simpler distributions into a single form, allowing a continuous range of possible shapes that includes all three of the simpler distributions: types I, II, and III. Types I, II, and III families are also known as the Gumbel, Frechet and 3-parameter Weibull distributions, respectively. We propose the use of the adaptable GEV distribution to characterize the extreme wind speeds associated to extreme meteorological events. Moreover, GEV allows the estimations of wind speed associated to a high return period (e.g. 50 yr wind speed return level). The PDF of the GEV distribution, with location parameter μ, scale parameter σ, and shape parameter $k\neq 0$ is

$$f(x;\mu,\sigma,k)=\left(\frac{1}{\sigma}\right)\exp\left(-\left(1+k\frac{(x-\mu)}{\sigma}\right)^{-(1/k)}\right)\left(1+k\frac{(x-\mu)}{\sigma}\right)^{-1-1/k}, \tag{3}$$

defined on $\{1+k(x-\mu)/\sigma\}>0$.

The shape parameter defines the upper tail distribution behavior. $k>0$ corresponds to the distribution Type II (heavy tail of the Fréchet domain of attraction) while $k<0$ corresponds to the Type III (bounded tail of Weibull domain of attraction). For $k=0$, corresponding to the Type I-Gumbel case, the PDF is

$$f(x|0,\mu,\sigma)=\left(\frac{1}{\sigma}\right)\exp\left(-\exp\left(-\frac{(x-\mu)}{\sigma}\right)-\frac{(x-\mu)}{\sigma}\right) \tag{3}$$

2.2. Wind profile

Wind speed at a specific height is needed to design wind turbines and wind farms. There are two sources that can provide wind information at several heights of interest for wind energy industry: in-situ measurements from meteorological masts, LIDAR and SODAR technologies, and simulated data from 3-D atmospheric numerical models. Vertical resolution of available data do not always agree with hub height and design necessities, thus mathematical wind profile expressions are usually fitted to data in order to evaluate wind speed at a particular hub height.

Wind profile is mainly determined by the surface roughness characteristics (i.e. frictional drag), the heat transfer, and the evaporation process. These factors are produced by the interaction between air masses with sea surface and the atmospheric boundary layer (ABL) thickness, and describe three situations of the atmospheric stability:

(i) Convective or unstable which is generated from heat transfer from warm ground surface. (ii) Stable, typically from cooling of the surface at night; and (iii) neutral, where the flow can be characterized by the combination of wind shear and no convection.

Some research in this field resulted in empirical wind profile expressions. They all start from the same point

$$\frac{\partial u}{\partial z}=\frac{u_*}{Kl} \tag{5}$$

Proposed by Panofsky (1973), where u is the wind speed, z is the height, u^* is the friction velocity, l is scale length and K is the von Karman constant ($\sim$0.4).

After some assumptions (more details in Peña and Gryning, 2008), wind speed at the ABL is obtained by

$$u=\frac{u_*}{k}\left[\ln\left(\frac{z}{z_0}\right)-\psi_m\left(\frac{z}{L}\right)\right] \tag{6}$$

where z_0 is the roughness length and ψ_m is an atmospheric stability function depending on height z and the Obukhov length $L.\psi_m$ function describes the convective properties of the air mass.

Wind energy industry works always within the first meters of the ABL. Although wind speed variations can be noticed depending on the atmospheric stability, they can be considered negligible within the height range wind industry works in (Holtslag, 1984). Some simplifications can be made to the complex expressions derived from expression (6), resulting in the logarithmic wind profile (Tennekes, 1973)

$$u=\frac{u_*}{k}\ln\left(\frac{z}{z_0}\right).$$

In order to simplify as much as possible, wind industry uses the potential wind profile. The potential wind profile, also named wind power law, resumes every physical information in only one parameter (Hsu et al., 1994), but it fits well to data in the first meters of the ABL (Gryning et al., 2007). All physical information is included in the parameter α, reducing the number of parameters to estimate into two, the wind speed at reference height (i.e. 10 m) and the exponent parameter α

$$u=u_{ref}\left(\frac{z}{z_{ref}}\right)^{\propto}. \tag{8}$$

There are several estimations methods to obtain the α-parameter value. Least-squares technique is often used in wind energy field because of its simplicity. In this case, a heterocedastic regression model is applied (more details, Mínguez et al. (2012).