A New Approach to Assess Wind Potential

Fozia Zaheer[1], Saif Uddin Jilani2, Muhammad Ahsan uddin[3], Ambreen Insaf[4], S. Mamnoon Akhtar[4] , Zaheer Uddin[2]
[1]Institute of Space Science and Technology, University of Karachi

[2]Department of Physics, University of Karachi

[3]Department of Economics, University of Karachi

[4]Department of Applied Physics, University of Karachi

Abstract:

Weibull Cumulative Distribution Function (C.D.F.) has been employed to assess and compare wind potentials of two wind stations Europlatform and Stavenisse of The Netherland. Weibull distribution has been used for accurate estimation of wind energy potential for a long time. The Weibull distribution with two parameters is suitable for modeling wind data if wind distribution is unimodal. Whereas wind distribution is generally unimodal, random weather changes can make the distribution bimodal. It is always desirable to find a method that accurately represents actual statistical data. Some well-known statistical methods are Method of Moment (MoM), Linear Least Square Method (LLSM), Maximum Likelihood Method (M.L.M.), Modified Maximum Likelihood Method (MMLM), Energy Pattern Factor Method (EPFM), and Empirical Method (E.M.), etc. All these methods employ Probability Density Function (PDF) of Weibull distribution, except LLSM, which uses Cumulative Distribution Function (C.D.F.). In this communication, we are presenting a newly proposed method of evaluating Weibull parameters. Unlike most methods, this new method employs a cumulative distribution function. A MATLAB® GUI-based simulation is developed to estimate Weibull parameters using the C.D.F. approach. It is found that the Mean Square Error (M.S.E.) is the lowest when using the new method. The new method, therefore, estimates wind power density with reasonable accuracy. Wind Power (W.P.) is estimated by considering four different Wind Turbine (W.T.) models for two sites, and maximum W.P. is found using Evance R9000.

Keywords: Weibull distribution, Weibull parameters, Maximum likelihood method, method of moments, Empirical method, Energy pattern method, Linear least square method, simulation method, MATLAB Simulation.

1. Introduction

The world is switching from the conventional methods of generating electricity to its generation through renewable energy. Wind energy is one of the best choices, especially for sites where the wind blows throughout the year with appreciable potential. Up till now, wind power generation plants have been installed in many parts of the world, such as France, the Netherlands, and Malaysia [1-4]. Wind direction and solar irradiance play a vital role in the determination of wind and solar potentials. The wind potential assessment of Marmara (Turkey) from 1991-1995 was carried out with hourly wind data [5]. In Chile, the wind power generation industry is growing so rapidly that it has made Chile the second-largest market in Latin America for wind power [6]. Irwanto et al. analyzed characteristics of wind distribution of two sites of Perlin (Malaysia) [7]. Wind power potential was calculated using Weibull distribution using daily and monthly wind speeds. Wind energy and power were examined as a function of the height at which the wind speed was recorded. It was concluded that the higher the height of the recorded station, the higher would be the wind density. Khahro et al. evaluated wind potential of Gharo, Sindh, Pakistan for 2003-2007, for which recorded wind speed data at the height of 30 meters was used [8]. An Energy of 11.220 GWh was estimated using wind turbine GE45.7. It was concluded that Gharo is one of the potential sites where a wind turbine can be installed [8]. Maatallah et al.assessed and evaluated generation of electricity through wind speed for Gulf of Tunis [8]. Four different methods were used to analyze wind potential using Weibull distribution with eight different wind turbines [9]. Razavieh et al.statistically investigated wind characteristics of wind speed distribution of two sites Sistan and Baluchestan of Iran [10]. Using the wind rose diagram, wind speed variation was shown, and the most dominant direction of wind speed was found. Khash and Nosratabad stations were proposed as more suitable stations for the generation of electricity. An average annual wind power density of 388 W/m^2 at a height of 40m was estimated [10]. Hasan et al used wind data obtained from a station at Zawiya in Libya at the height of 50m to assess wind energy. Annual wind energy of 2.7 GWh was evaluated using a 750kW wind turbine [11]. Fyrippis et al.performed statistical analysis using Weibull and Rayleigh distributions to investigate wind potential of Coronas village of Naxos Island, Greece. An annual average power density was calculated, and it was concluded that the Weibull distribution fits wind speed data better than the Rayleigh distribution [12]. Kwon presented a framework to examine the wind potential and wind turbine through uncertainty analysis. A probability model was proposed to find various parameters associated with wind data, including Weibull parameters. The empirical probability model and Monte Carlo simulations were utilized to estimate annual power generated [13]. Chang estimated wind potential using the maximum entropy principle together with several mixed probability distributions. Two new mixed distributions were proposed, Gamma-Weibull and truncated normal distribution. Using five different distributions, wind potential was examined in Taiwan [14]. Recently, Sumair et al. proposed a method to evaluate Weibull parameters and assessed wind potential in Southern Punjab, Pakistan [15]. Jung and Schindler published a review on wind speed distribution selection; it is mentioned that Weibull distribution was the most evaluated distribution [16].

2. Material and Method:

2.1. Distribution and determination of its parameters

Wind speed is a random variable; the most frequently used probability distribution for this random variable is the Weibull distribution [17-19]. Wind distribution usually follows a bell-shaped curve, and the Weibull distribution is the most suitable probability distribution to bell-shaped model data. The Weibull distribution is classified as either a three-parameter distribution [20] or a two-parameter distribution [21]. The Weibull distribution with two parameters $\alpha \; and \; \beta$ is given by the following probability density function (PDF) [22].

$$f(v) = \left(\frac{\alpha}{\beta}\right)\left(\frac{v}{\beta}\right)^{\alpha-1} \exp\left[-\left(\frac{v}{\beta}\right)^{\alpha}\right] \tag{1}$$

The cumulative distribution function (C.D.F.) plays an essential role in distributing probability to various distribution events. The C.D.F. of Weibull distribution is given by [23];

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

The parameter α is a dimensionless quantity known as the shape parameter, while the parameter β has a dimension of wind speed and is known as scale parameter [24].

Following are the methods which have been employed in this work to find the Weibull parameters. The Weibull parameter will be used to draw PDFs and to obtain wind potential for the two sites.

2.1.2. Method of Maximum Likelihood (MML)

Weibull parameters can be found by fitting time-series wind data by the maximum likelihood method [25]. The Likelihood function is a function of wind speed, i.e., of Weibull pdf with two parameters. Maximization of the likelihood function concerning both the parameters will yield the following two equations. An iterative method is used to solve equation (3) to find the value of the parameter (α), which is further used in equation (4) to find the second parameter (β).

$$\frac{1}{\alpha} = \left[\frac{\sum_{i=1}^{n} v_i^{\alpha} \ln(v_i)}{\sum_{i=1}^{n} v_i^{\alpha}} - \frac{\sum_{i=1}^{n} \ln(v_i)}{n}\right] \tag{3}$$

$$\beta = \left(\frac{1}{n}\sum_{i=1}^{n} v_i^{\alpha}\right)^{\frac{1}{\alpha}} \tag{4}$$

2.1.3. Method of Moments (MoM)

In this method, the parameters ($\alpha\ and\ \beta$) are found by the first moment about the origin (average wind speed ($\bar{v}$)) and the second moment about means (standard deviation (σ)). It is an alternate method to the maximum likelihood method. Following are the equations for $\bar{v}\ and\ \sigma$ which are used to find parameters of Weibull distribution by the method of moments [26] (Teimouri *et al.* 2013),

$$\bar{v} = \beta \Gamma\left(1 + \frac{1}{\alpha}\right) \tag{5}$$

$$\sigma = \beta\left[\Gamma\left(1 + \frac{2}{\alpha}\right) - \Gamma^2\left(1 + \frac{1}{\alpha}\right)\right]^{\frac{1}{2}} \tag{6}$$

2.1.4. Linear Least Square method (LLSM)

In this method, the PDF of Weibull distribution is converted into the equation of a straight line, and then the least square method is used to find the best fit of the line [27]. The slope and y-intercept are used to calculate parameters of Weibull distribution, taking the double log of the PDF to get the following equation. This equation looks like $y = mx + c$, where $x = lnv$ and $y = ln\left(-ln\left(1 - F(v)\right)\right)$. Here $slope = m = \alpha$ and $y - intercept = c = -\alpha ln\beta$. The least square method gives both the parameter of Weibull distribution.

$$\ln\left(-ln\left(1 - F(v)\right)\right) = \alpha lnv - \alpha ln\beta \tag{7}$$

2.1.5. Empirical Method (E.M.)

The Empirical method is the simplest method of finding Weibull parameters. It is a particular case of the method of moments [28]. Equations (9) and (10) are used to calculate parameters $\alpha\ and\ \beta$.

$$\alpha = \left(\frac{\bar{v}}{\sigma}\right)^{1.086} \tag{8}$$

$$\bar{v} = \beta \Gamma \left(1 + \frac{1}{\alpha}\right) \tag{9}$$

2.1.6. Energy Pattern Factor Method (E.P.M.)

Energy pattern factor (E_{pf}) is the ratio of the average value of cube of the wind speed ($\overline{v^3}$) and cube of average wind speed ($\bar{v}^3$). The energy pattern factor is used in the following equation to find parameter α,

$$\alpha = 1 + \frac{3.69}{\left(E_{pf}\right)^2} \tag{10}$$

To calculate β, this method uses the same formula as given in the empirical method.

The value of E_{pf} depends on wind characteristics and wind distribution; it has different values for different wind stations. The maximum value of 6 occurs for polar regions [29].

2.1.7. New method for Weibull parameters estimation (Simulation of C.D.F.):

All existing methods for estimation of Weibull parameters, including the ones discussed above, make use of the Weibull probability density function except for the linear least square method and graphic method that employ the cumulative distribution function. The newly proposed method in this study is also based upon C.D.F. The simulation overlaps the theoretical C.D.F. curve on the C.D.F. of recorded wind speed data. A screenshot of the MATLAB simulation program is shown in fig. 5.

(i) The wind data of the potential site is converted into a probability distribution (PDF).
(ii) The PDF is converted into a cumulative probability distribution (C.D.F.).
(iii) A Weibull distribution C.D.F. is generated by MATLAB simulation.
(iv) Two buttons control Weibull C.D.F.; these buttons vary the values of Weibull parameters.
(v) The simulation continues until two C.D.F.s overlaps completely, and Mean Square Errors (M.S.E.) and Chi-square values are their lowest.

2.2. Average speed and Wind Power Density (W.P.D.)

Wind power density varies as the cube of wind speed and measures available wind energy at a potential wind site. The average value of wind speed and wind power densities can be found by Weibull parameters as given below

$$v_{ave} = c\Gamma \left(1 + \frac{1}{k}\right) \tag{11}$$

$$WPD = \frac{1}{2}\rho c v^3 \tag{12}$$

here ρ is the air density in kg/m^3.

2.2.1. Wind Power (W.P.)

The kinetic energy in the wind is converted into electrical energy using wind turbines. The kinetic energy in the wind is proportional to the cube of wind speed and swept area of turbine and expressed as:

$$WP = \frac{1}{2}\rho A c_P v^3 \tag{13}$$

here, $C_{.P.}$ is the maximum power coefficient, ranging from 0.25 to 0.45. It is dimensionless (theoretical maximum = 0.59. While A is Rotor swept area (m^2)

2.3. Wind potential sites

To check the reliability of new methods, it is applied to wind distribution to estimate wind power densities from wind data of two wind sites Europlatform and Stavenisse of Netherland. Hourly wind data recorded at the height of 10m was used to compare the wind potential of two sites.

2.3.1 Europlatform

Europlatform is a multipurpose platform situated about 30 km from Hoek van (see fig. 1). The platform is of significance as it is a beacon for ships, and it is also used for wave and meteorological measurements. These measurements are an automatic weather station for the Royal Netherlands Meteorological Institute (KNMI). Some of the meteorological measurements taken at the station since 1977 are temperature, wind speed, wind direction, wave height, air pressure, and air humidity.

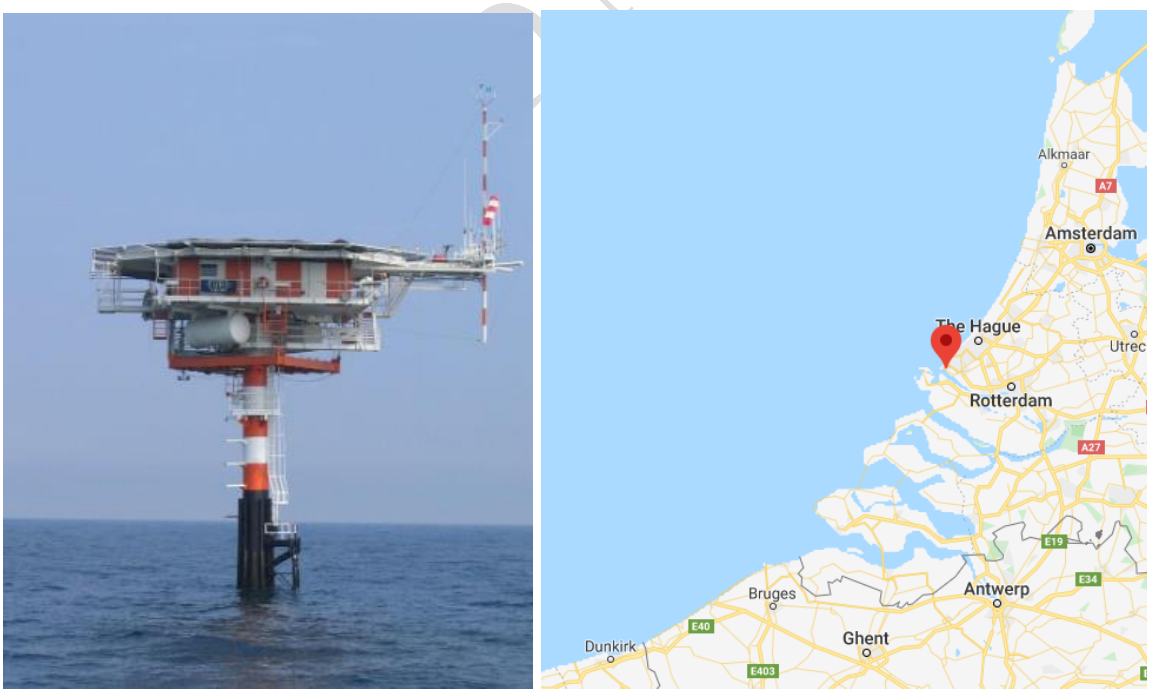


Fig. 1. Weather station Europlatform and map showing the location of Hoek van (https://www.windopzee.net/en/locations/europlatform/.)

2.3.2 Stavenisse

Stavenisse is situated in the municipality of Tholen, which is in the Zeeland province of the Netherlands. It is 22 km to the west of Bergen op Zoom. As of 2018, the town of Stavenisse has 1380 residents and an area of 0.448 km^2. The general area called Stavenisse, containing the town and the outskirts and countryside, has a population of 1798 people.

Fig. 2. Map of Stavenisse (https://www.citypopulation.de/en/netherlands/zeeland/tholen/1495__stavenisse/.)

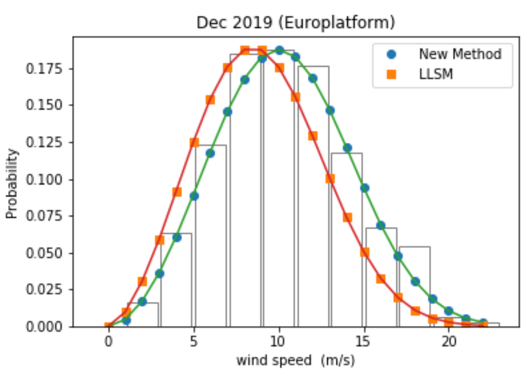


Fig. 3. Pdf generated from new method and LLSM

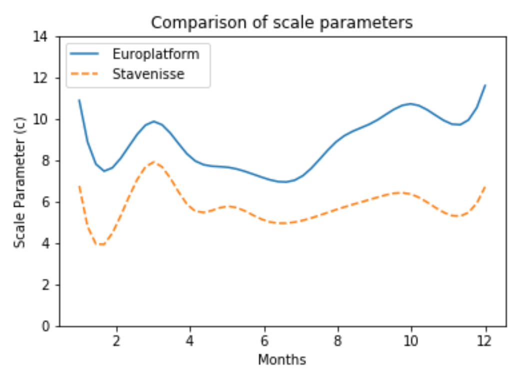


Fig. 4. Comparison of scale parameters

2.4.1 Simulation of C.D.F. curve

This optimization tool comes with an easy-to-use G.U.I., designed using MATLAB® and requires a MATLAB® runtime to execute. This G.U.I. provides a window where optimization can be achieved. Users can load an excel data file by pressing the load button. As soon as data is loaded, initial values of c and k are estimated, and probabilities and fitness parameters are computed. To understand the optimization process, three graphs are included in G.U.I. These graphs include plots of residual error, histogram, pdf, and plot of C.D.F. & cumulative relative frequency. The c+, c-, k-, k+ buttons are used to vary the values of parameters to be optimized. Value of increment/ decrement is 0.01. Output fields S.S.E. and Chi-square are fitness statistics and provide an idea about the goodness of fit.

2.4.2. Optimization steps

1. Load a data file by pressing the load button and providing a path of the excel data file.
2. Increase the value of c and observe the graphs and values of S.S.E. and χ^2. If these values decrease with increasing value of c, then continue to increase c until S.S.E. and χ^2 get their minimum, otherwise, decrease the value of c to minimize S.S.E. and χ^2 .
3. Now repeat step 2 for the value of k.

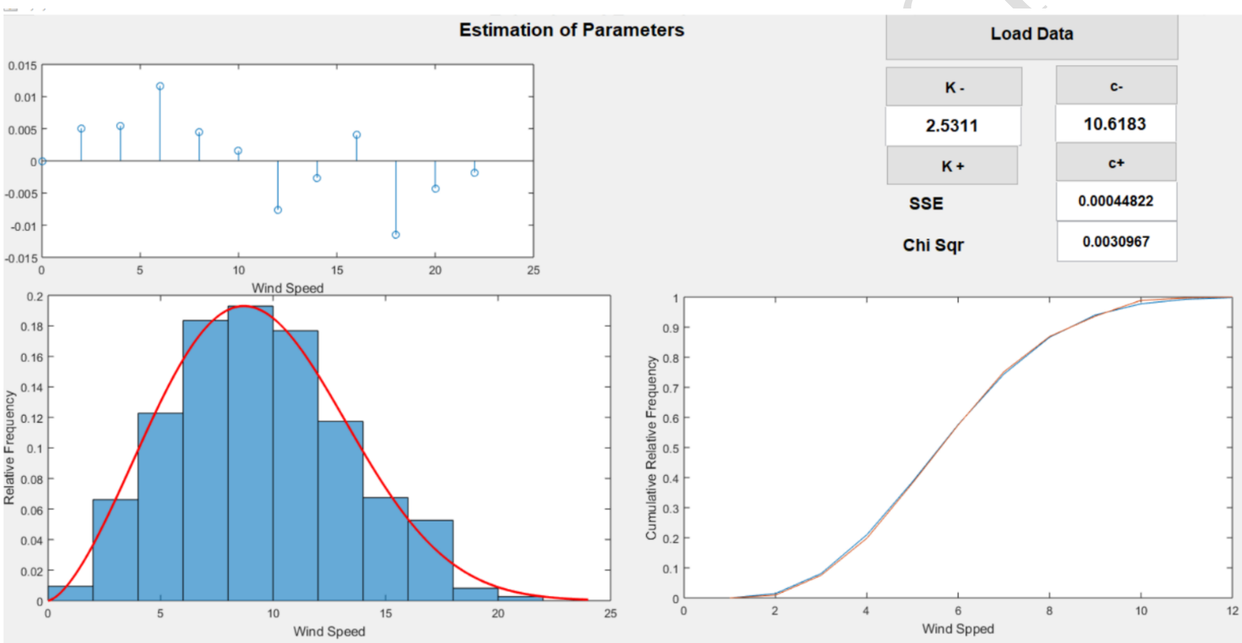


Fig. 5. Simulation of C.D.F. curve of Weibull distribution

3. Results and Discussion

Wind potentials of two wind sites (Europlatform and Stavenisse) of The Netherlands have been calculated using Weibull distribution. The Weibull parameters are calculated using a newly proposed method. The method is based on the simulation of C.D.F. of Weibull parameters. The simulated C.D.F. of Weibull distribution is produced and overlapped on C.D.F. of recorded wind speed data. All the existing methods for determining Weibull distribution parameters use pdf, except for LLSM, which uses C.D.F. of Weibull distribution. This simulation method is a second method that uses C.D.F. The results obtained by LLSM are less reliable than M.L.M. In fig. 3, a histogram is drawn by recorded wind speeds. Two curves are drawn using Weibull parameters found by simulation method and LLSM (both methods employ C.D.F. of the distribution). The curve in blue is the one obtained from the simulation process; the other curve is obtained from LLSM parameters. It is clear from the graph that the new method (simulation method) produces a better representation of recorded data than LLSM. Tables I and II show a detailed statistical comparison between the newly proposed method and other methods mentioned above. Figure 6 and 7 pdfs (generated using equation (1)) for wind distribution of Europlatform and Stavenisse sites, respectively, are given. These pdfs are generated from the values of the parameters, 'k' and 'c'. The values of the parameters have been calculated using the methods LLSM, E.P.M., EM, MoM, M.L.M., and the newly proposed method. Each fig. 6 and 7 contains 12 pdfs and the histograms generated from the recorded wind data for 2019 from January to December. If we look at figs. 6 and 7, we see that theoretical pdfs generated from calculated values of 'k' and 'c' fit nicely on the histogram of recorded wind speeds distribution. However, the pdf generated from the new simulation method covers only the region where wind speed has a reasonable value; this is the region that can be exploited to generate electricity. The other pdfs cover either a portion of the histogram or complete histogram; this means the pdf of the new method is a good choice for the assessment of wind potential.

The new method based on the simulation technique is used to find Weibull parameters. MATLAB GUI is developed to simulate C.D.F. of observed wind distribution. Each of the Figs. 8 and 9 illustrate two plots of C.D.F.s (see equation (2), C.D.F. is a function of parameters 'k' and 'c') computed by the new method along with observed frequencies for wind distribution of the sites, respectively. The wind speed data is converted into frequency and probability distribution; a new probability distribution is generated by MATLAB simulation process in which shape and scale parameters are varied till both the C.D.F.s overlap completely, and the errors acquire their corresponding minima. Two simulation errors Mean Square Error (M.S.E.) and Chi-square statistic, are calculated to compare the effectiveness of the simulation process. The details are shown in tables I and II.

In both tables, the first two columns show 'k' and 'c' values, and the next two columns show errors M.S.E. and Chi-square. The last two columns show average wind speeds and wind power densities, respectively. With few exceptions, M.S.E. and Chi-square values calculated from the new method are the lowest indicating the accuracy of the fit by the new method. It also indicates the wind power densities calculated by the new method are more reliable. The maximum and minimum values (969.50 and 223.23 W/m^2) of W.P.D. for Europlatform occur in December and June, respectively. In March and February, the maximum and minimum values (393.27 and 79.75 W/m2) of W.P.D. for Stavenisse, respectively. According to Mostafaeipour (Mostafaeipour *et al.* 2011), the wind potential areas can be classified with respect to power densities as follows: (i) poor resource areas have WPD < 100 W/m^2, (ii) marginal resource areas have 100 < WPD < 300 W/m^2, (iii) good resource areas have 300 < WPD < 700 W/m^2, and (iv) excellent resource areas have WPD > 700 W/m^2 [30] According to this classification, the site Europlatform has excellent potential, whereas Stavenisse has a marginal resource. The scale parameter measures average wind speed (average wind speed at wind energy site is proportional to the value of scale parameter). Fig. 4. gives a comparison of scale parameters of two sites Europlatform and Stavenisse. The scale parameter measures wind speed, and wind power density is proportional to the cube of the scale parameter. The value of the scale parameter of Europlatform remains greater than corresponding values at Stavenisse throughout the year. It also verifies that the site Europlatform has greater potential than Stavenisse. Both the curves have the same behavior. There exists a linear relationship between scale parameters and average wind speed. It is found that the slope of the line is almost the same (0.883) for both sites.

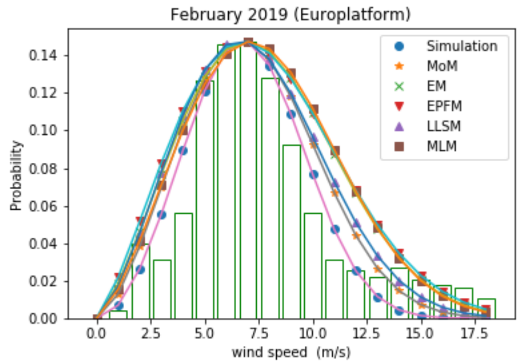


Fig. 6a.

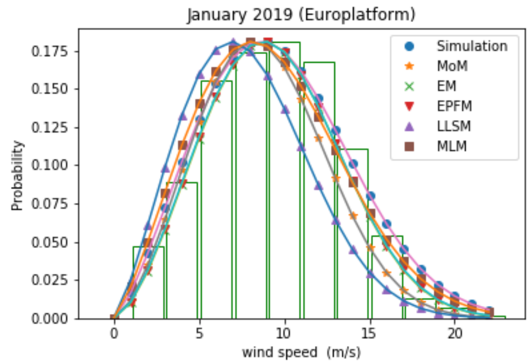


Fig. 6b.

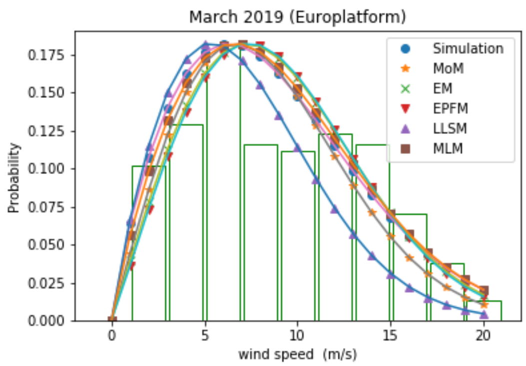


Fig. 6c.

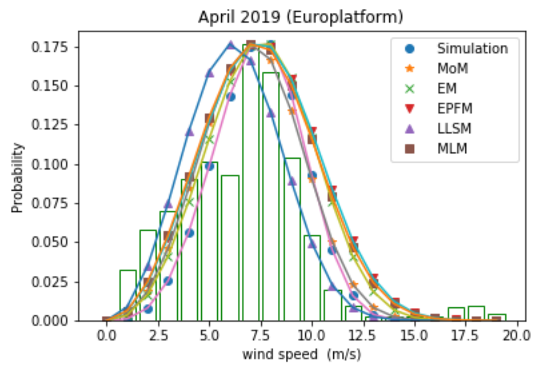


Fig. 6d.

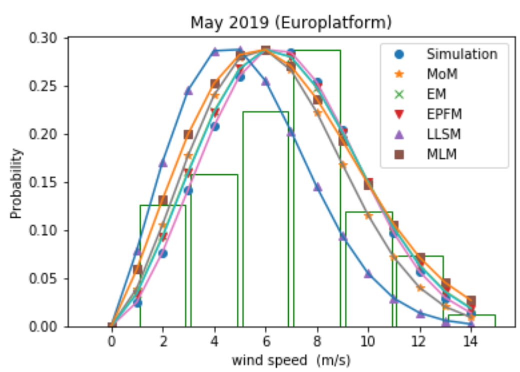
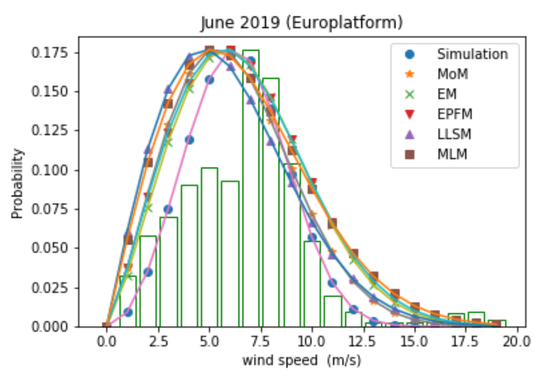


Fig. 6e.



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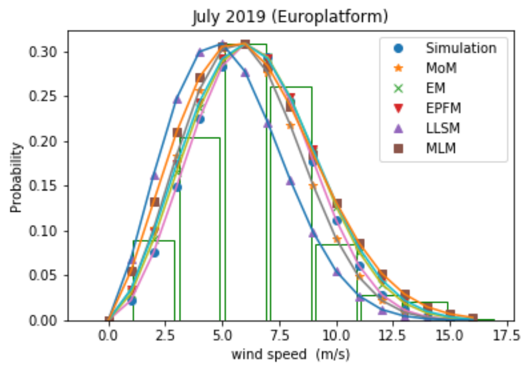


Fig. 6g.

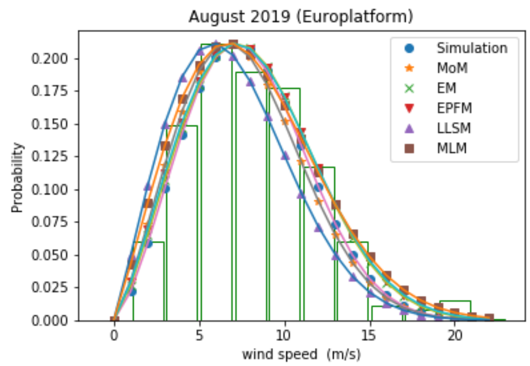


Fig. 6h.

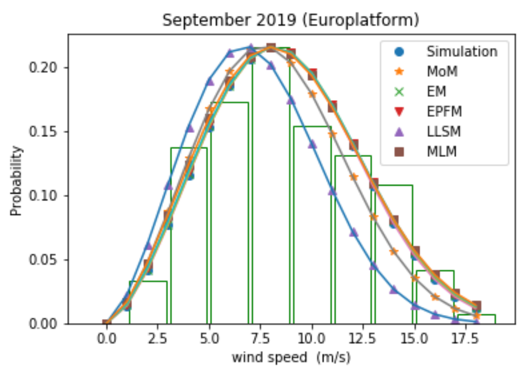


Fig. 6i.

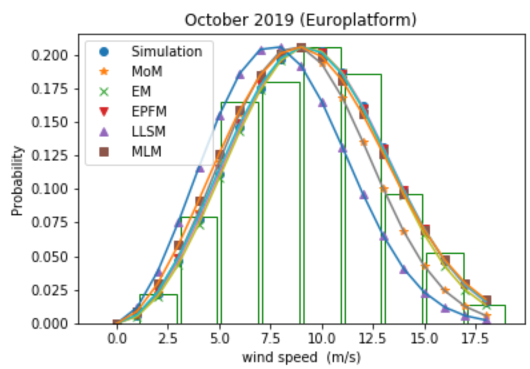


Fig. 6j.

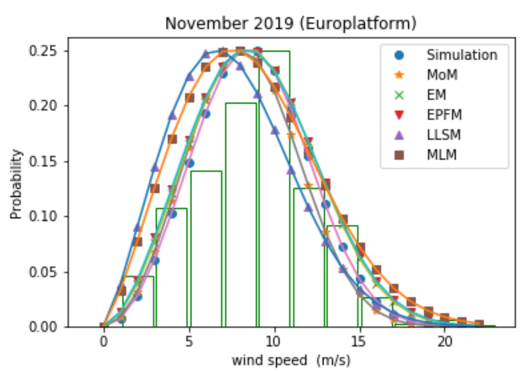


Fig. 6k.

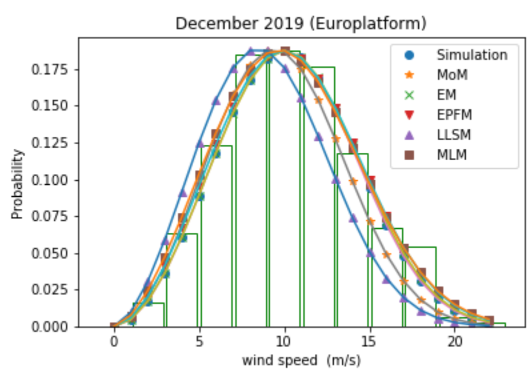


Fig. 6l.

Fig. 6. PDFs of Weibull distribution generated by six methods and histogram of recorded wind speed at Europlatform

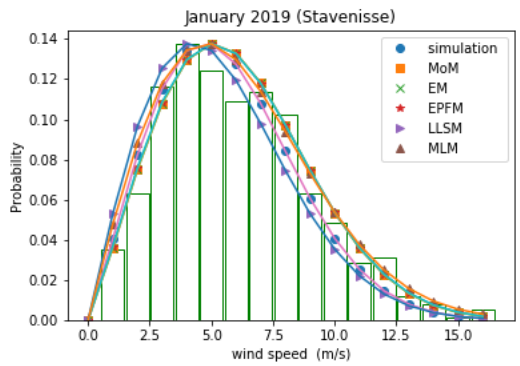


Fig. 7a.

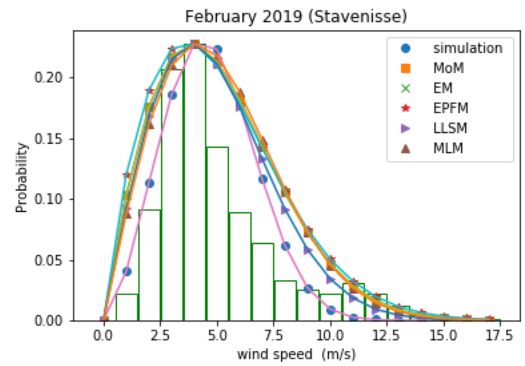


Fig. 7b.

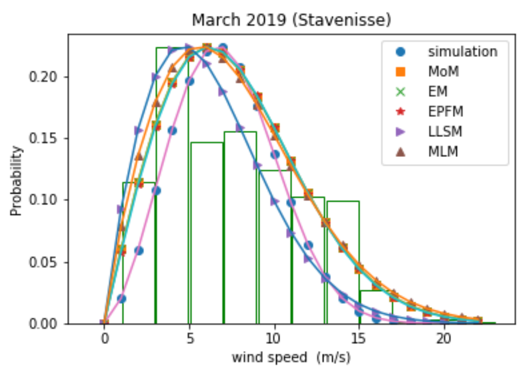


Fig. 7c.

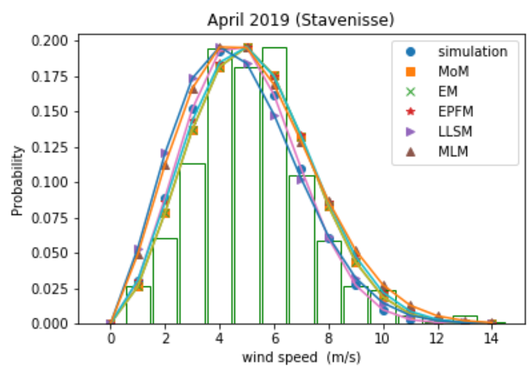


Fig. 7d.

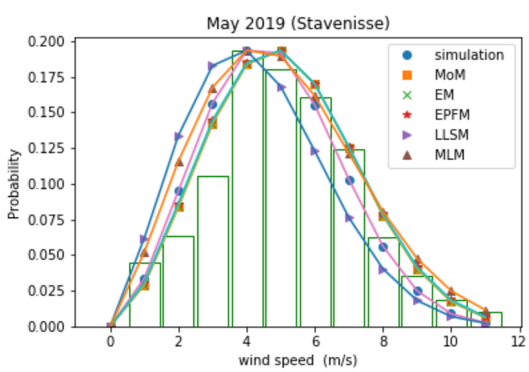
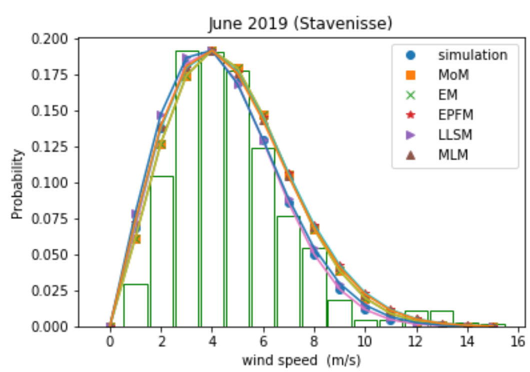


Fig. 7e.



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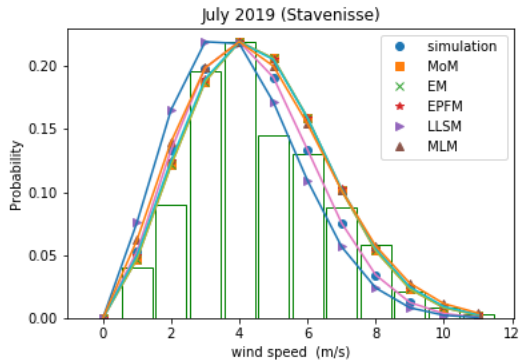
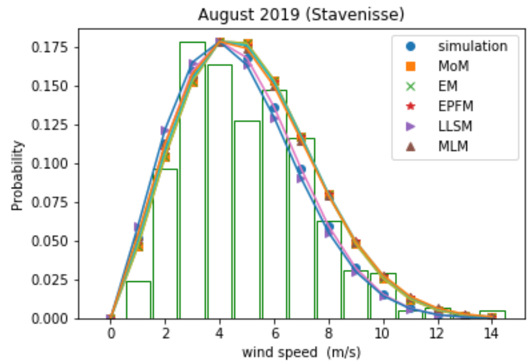


Fig. 7g.



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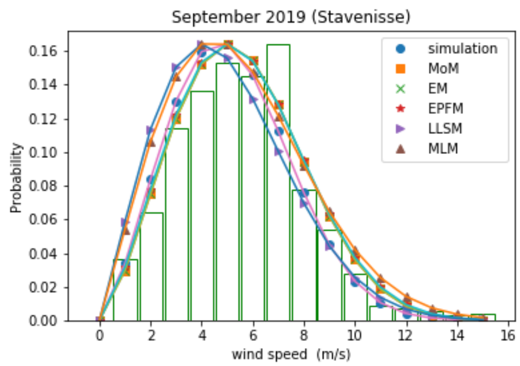


Fig. 7i.

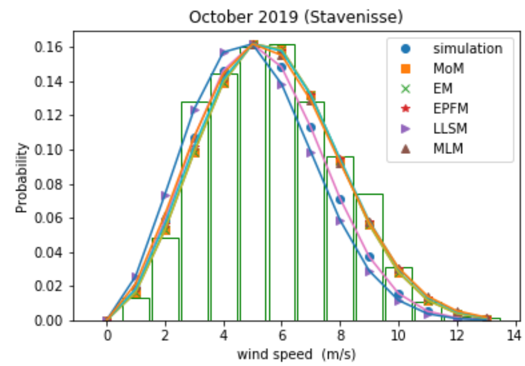


Fig. 7j.

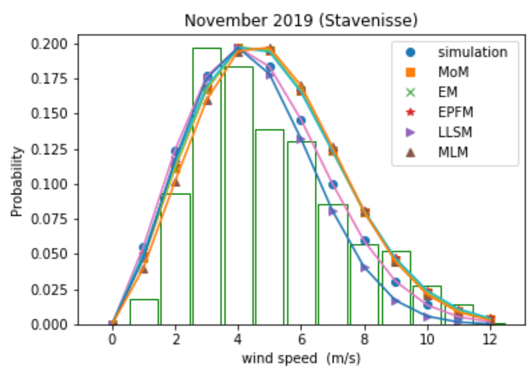


Fig. 7k.

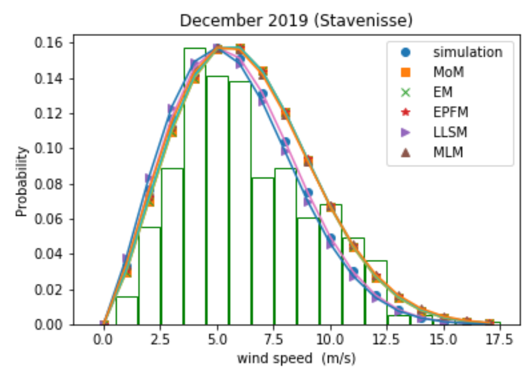


Fig. 7l.

Fig. 7. PDFs of Weibull distribution generated by six methods and histogram of recorded wind speed at Stavenisse

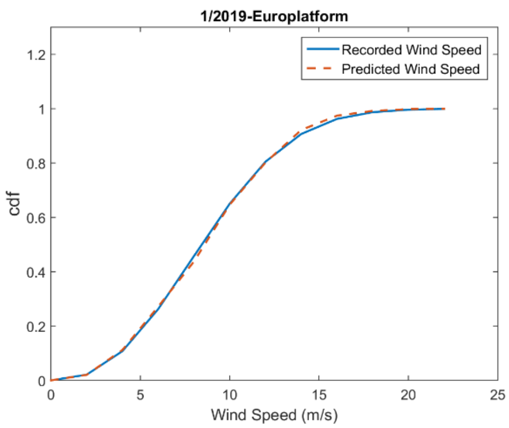


Figure 8a

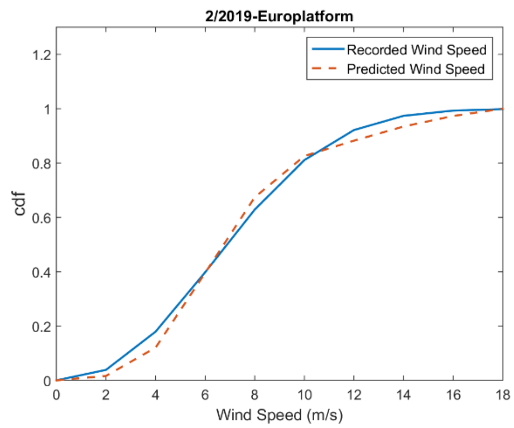


Figure 8b

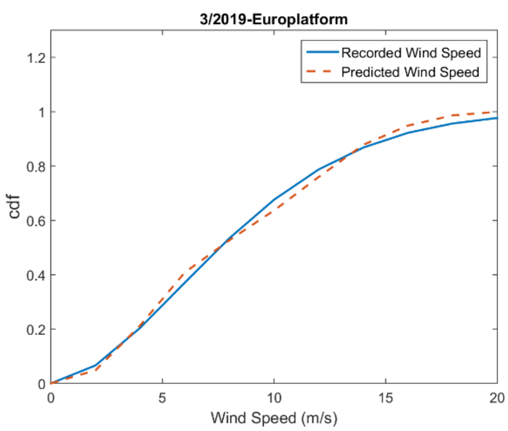


Figure 8c

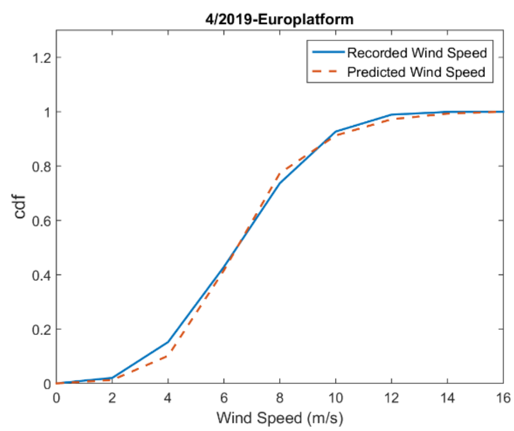
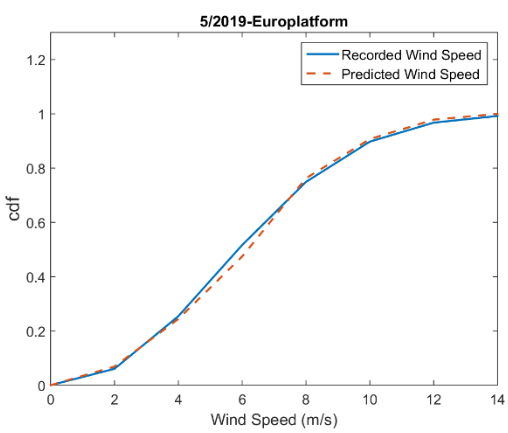


Figure 8d



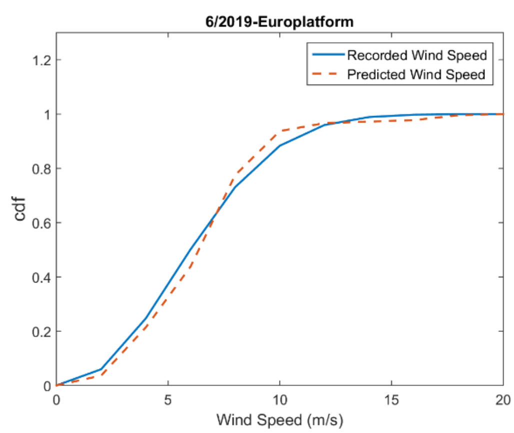


Figure 8e

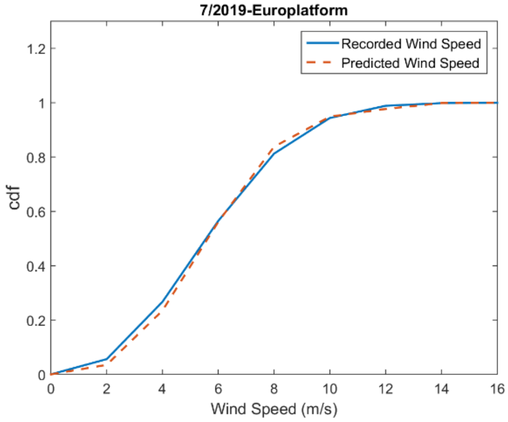


Figure 8f

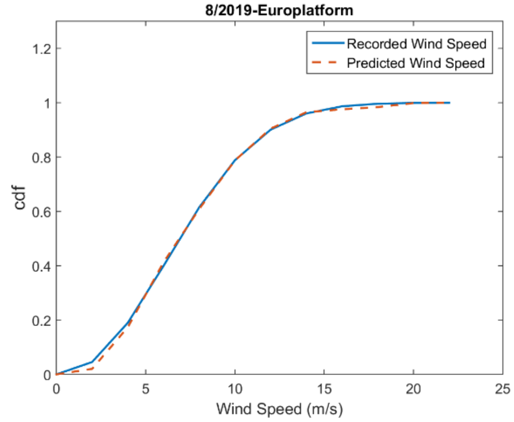


Figure 8g

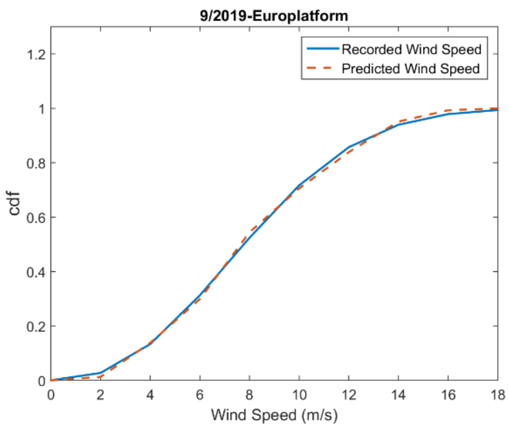


Figure 8h

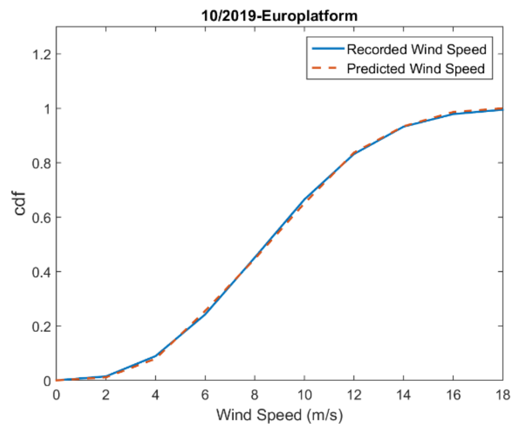


Figure 8i

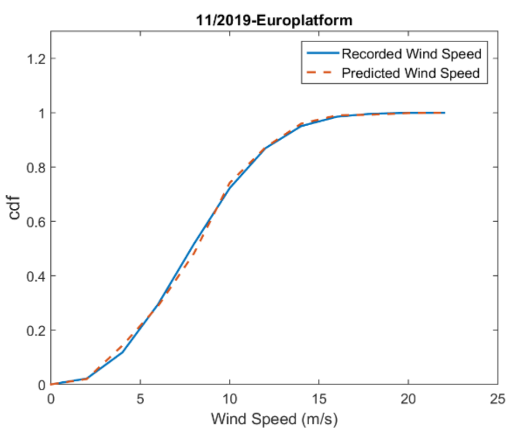


Fig. 8k

Figure 8j

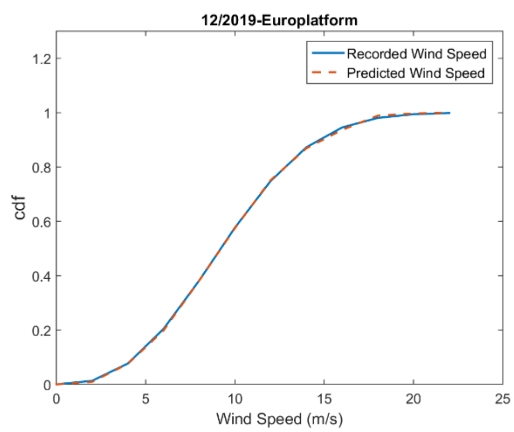


Fig. 8l

Fig. 8. C.D.F.s of Weibull distribution generated by new method and relative cumulative frequency of recorded wind speed at Europlatform

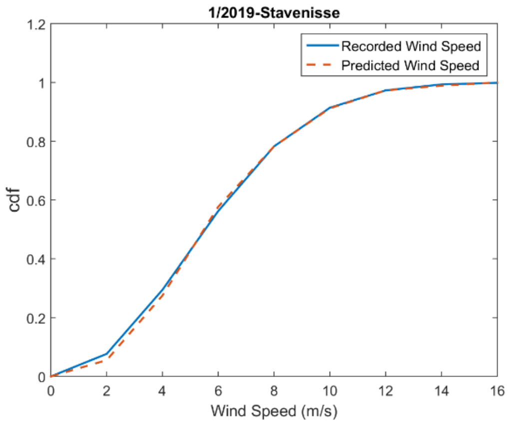


Fig. 9a

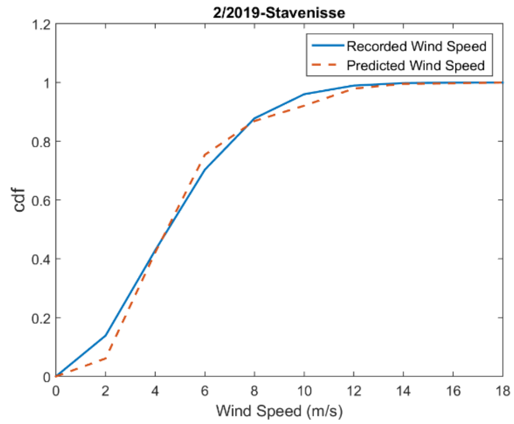


Fig. 9b

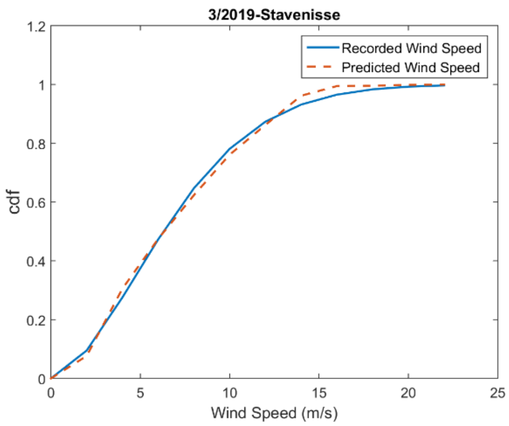


Fig. 9c

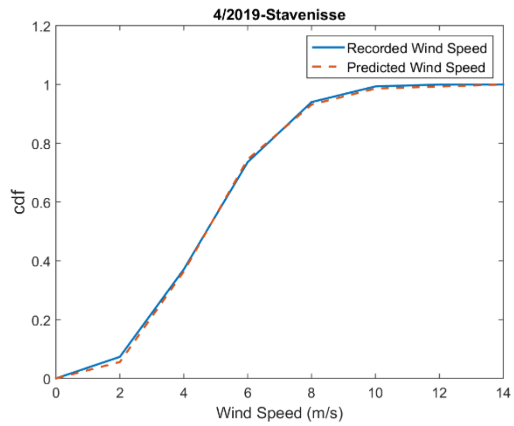


Fig. 9d

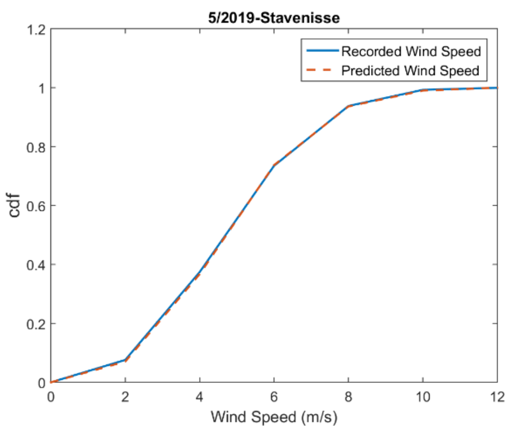


Fig. 9e

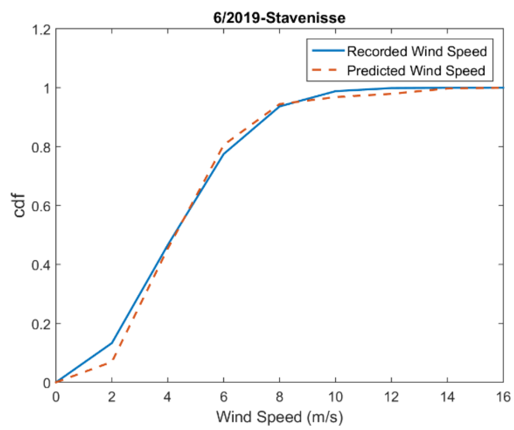


Fig. 9f

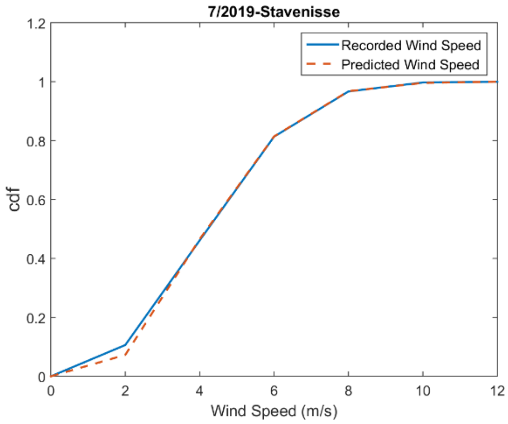


Fig. 9g

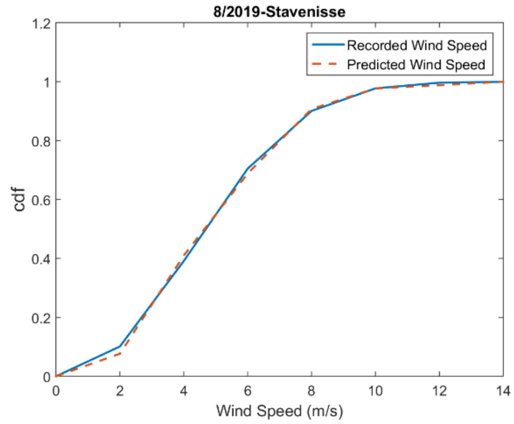


Fig. 9h

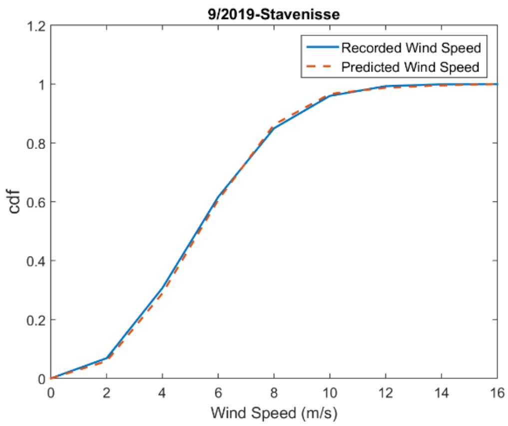


Fig. 9i

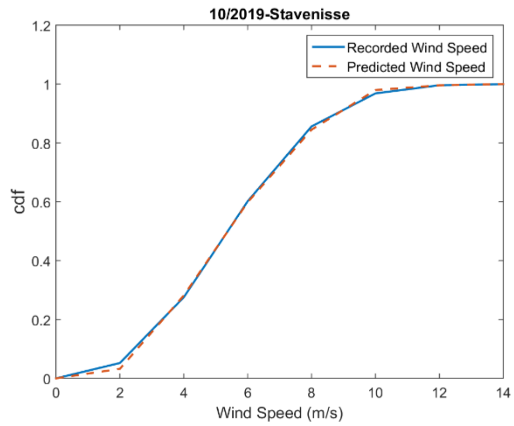


Fig. 9j

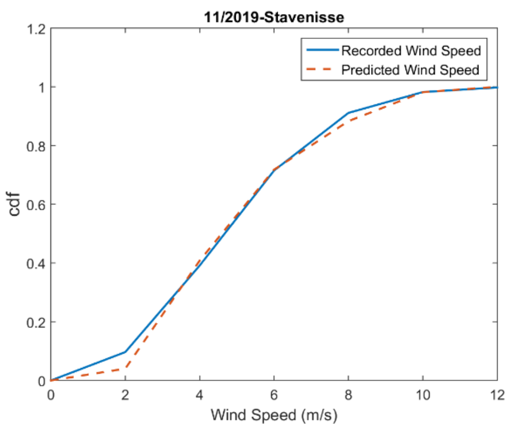


Fig. 9k

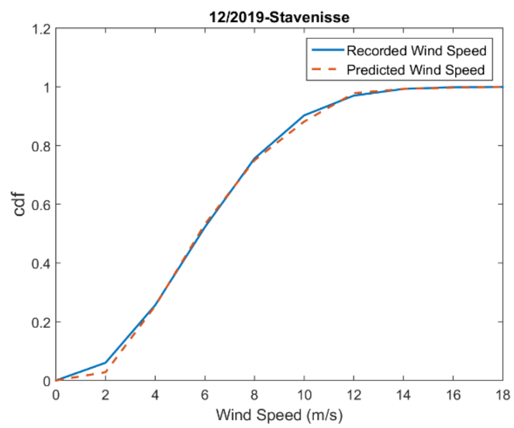


Fig. 9l

Fig. 9. C.D.F.s of Weibull distribution generated by a new method and relative cumulative frequency of recorded wind speed at Stavenisse

The energy produced from a Wind Turbine (W.T.) is estimated using different W.T.s provided by the manufacturers. The relevant information of some W.T. manufacturers is shown in table III (E.W.T.; PE; SkyStream; W.T.). The power produced by a W.T. depends on the wind speed's strength at the site, rated speed at which W.T. can produce rated power, swept area of W.T., and efficiencies. Therefore, evaluation of power generated by W.T. is a challenging method, and hence it is approximated by using equation 13. Table IV and V show the estimated W.P. at sites Europlatform and Stavenisse, respectively, by taking monthly wind speeds into account and using W.T. models represented in Table III. W.P. is estimated by considering four different W.T. models for two sites, and maximum W.P. is found by using Evance R9000. It is also observed that the estimated W.P. is maximum in December at Europlatform and in March at Stavenisse.

4. Conclusion

The Weibull parameters [33] should be known with reasonable accuracy to install a wind turbine with optimum efficiency and minimum generation cost. The determination of the correct value of wind potential links with the determination of correct wind distribution. A proper modeling scheme can serve this purpose. A new method is proposed to determine the reasonably accurate wind potential of a site. The new method is based on the simulation of C.D.F. The MATLAB GUI is developed to simulate the C.D.F. The method is used to calculate and compare the wind potentials of Europlatform and Stavenisse of The Netherlands. The pdfs are drawn from ‘k’ and ‘c’ values of Weibull distributions.

- The newly proposed method is the best to model wind distribution. Among six different methods for estimation of Weibull parameters, the minima of M.S.E. and Chi-square values occur for the new method. Fig. 8 and 9 give simulated and recorded wind distribution C.D.F.s. The overlapping of the two graphs is excellent.
- Unlike pdfs generated by other methods covering the whole range of histograms, the pdf generated by the new method covers the region of highly probable wind speeds, i.e., the region that can effectively be used to generate electricity (see figs 5b, 5f, and 6b). The values of shape parameters in such cases are quite different from those found by other methods. The new method gives an accurate picture of available wind energy potential.
- The values of ‘k’ and ‘c’ calculated by the new method are reliable, and wind potential and wind power density calculated by these values are reasonably accurate.
- The scale parameter calculated by LLSM and M.L.M. has the same values for both stations.
- As calculated by the new method, the wind speed ranges from 6.37 m/s to 10.33 m/s at Europlatform and from 4.29 m/s to 7 m/s at Stavenisse.
- The Stavenisse station has a fair resource of wind potential because most of the time, the power density is less than 200 W/m^2.
- The Europlatform station is a suitable candidate for the installation of wind power plants because most of the time the wind speed at Europlatform is more than 7 m/s.
- Maximum wind potentials are seen in the months of December and March for the sites Europlatform and Stavenisse, respectively.
- Minimum wind potentials are seen in the months of June and February for the sites Europlatform and Stavenisse, respectively
- The value of the shape parameter for Europlatform is greater than the value at the Stavenisse throughout the year (see fig. 4). Since c is a measure of average wind speed (a linear relationship exists between c and average wind speed; the slope is approximately the same for both the sites), the wind potential at Europlatform is higher than Stavenisse throughout the year.
- W.P. is estimated by considering four different W.T. models (table III) for two sites, and maximum W.P. is found using Evance R9000 (shown in tables IV and V).

Declarations

Authors have no competing interests to declare.

Funding

Authors did not receive any funding or financial support to conduct this study.

Table I: The Weibull parameters, average wind speeds and wind power densities for January to December 2019 for Europlatform.

		k	c	Chi2	MSE	Vave	WPD
Jan	New method	2.375	10.874	0.020033	0.000130	9.64	899.08
	MoM	2.594	9.893	0.051998	0.000501	8.79	638.49
	EM	2.606	10.595	0.02015	0.000168	9.41	782.12
	EPFM	2.589	10.597	0.019775	0.000163	9.41	785.64
	LLSM	2.306	8.856	0.146321	0.001495	7.85	496.63
	MLM	2.306	10.395	0.040491	0.000253	9.21	803.14
Feb	New method	2.937	7.81	0.147679	0.000251	6.97	294.48
	MoM	2.594	8.135	0.232803	0.000447	7.23	355.01
	EM	2.372	8.732	0.429112	0.000819	7.74	465.99
	EPFM	2.289	8.737	0.489939	0.000899	7.74	479.66
	LLSM	2.446	8.233	0.315073	0.000592	7.30	382.15
	MLM	2.446	8.821	0.41225	0.00081	7.82	470.02
Mar	New method	1.8	9.86	0.066332	0.000722	8.77	883.39
	MoM	2	9.479	0.087034	0.000891	8.40	693.47
	EM	2.023	10.178	0.075125	0.000825	9.02	848.31
	EPFM	2.066	10.18	0.079385	0.000870	9.02	831.00
	LLSM	1.862	8.147	0.153889	0.001442	7.23	477.50
	MLM	1.862	10.032	0.066492	0.000723	8.91	891.55
Apr	New method	3.902	8.152	0.077364	0.000685	7.38	306.43
	MoM	3.322	7.933	0.128208	0.001227	7.12	294.42
	EM	3.315	8.412	0.130693	0.001653	7.55	351.27
	EPFM	3.039	8.447	0.215009	0.002528	7.55	367.18
	LLSM	3.027	7.011	0.441481	0.004832	6.26	210.29
	MLM	3.027	8.342	0.208616	0.002393	7.45	354.23
May	New method	2.651	7.657	0.067058	0.001566	6.81	292.29
	MoM	2.472	7.114	0.094265	0.002348	6.31	244.79
	EM	2.487	7.629	0.071688	0.001702	6.77	300.68
	EPFM	2.499	7.628	0.070861	0.001689	6.77	299.61
	LLSM	2.218	5.933	0.278811	0.006648	5.25	154.14
	MLM	2.218	7.489	0.107205	0.002334	6.63	310.00
Jun	New method	2.988	7.139	0.175457	0.000665	6.37	223.23
	MoM	2.251	6.992	0.423546	0.001246	6.19	249.19

	EM	2.27	7.509	0.7338	0.001257	6.65	306.55
	EPFM	2.2	7.51	0.849837	0.001368	6.65	314.81
	LLSM	1.996	6.71	0.59417	0.001702	5.95	246.51
	MLM	1.996	7.347	1.074687	0.001715	6.51	323.59

		k	c	Chi2	MSE	Vave	WPD
Jul	New method	2.8	7.17	0.028874	0.000233	6.38	233.07
	MoM	2.625	6.781	0.040214	0.000634	6.02	204.17
	EM	2.636	7.26	0.040945	0.000411	6.45	249.96
	EPFM	2.561	7.266	0.050479	0.000537	6.45	254.94
	LLSM	2.329	5.987	0.187605	0.003462	5.30	152.27
	MLM	2.329	7.131	0.092127	0.001154	6.32	257.30
Aug	New method	2.44	8.936	0.028816	0.000215	7.92	489.47
	MoM	2.314	8.584	0.040214	0.000634	7.61	451.04
	EM	2.332	9.217	0.040945	0.000411	8.17	555.05
	EPFM	2.288	9.219	0.050479	0.000537	8.17	563.70
	LLSM	2.111	7.911	0.187605	0.003462	7.01	381.96
	MLM	2.111	9.07	0.092127	0.001154	8.03	575.64
Sep	New method	2.6	9.85	0.030464	0.000378	8.75	629.33
	MoM	2.573	9.238	0.051469	0.000541	8.20	522.45
	EM	2.585	9.897	0.030968	0.00037	8.79	640.60
	EPFM	2.558	9.9	0.031899	0.000359	8.79	645.32
	LLSM	2.508	8.22	0.157943	0.001592	7.29	374.04
	MLM	2.508	9.852	0.034216	0.000343	8.74	643.99
Oct	New method	2.88	10.71	0.008321	0.000144	9.55	766.24
	MoM	2.939	9.997	0.045999	0.000555	8.92	617.43
	EM	2.942	10.66	0.010416	0.000172	9.51	748.26
	EPFM	2.841	10.675	0.008487	0.000143	9.51	763.69
	LLSM	2.713	9.014	0.159615	0.00191	8.02	470.78
	MLM	2.713	10.533	0.014776	0.000188	9.37	751.14
Nov	New method	2.97	9.8	0.055009	0.000592	8.75	578.97
	MoM	2.939	9.343	0.078733	0.000867	8.34	504.01
	EM	2.724	9.993	0.093311	0.000762	8.89	640.04
	EPFM	2.674	9.999	0.110171	0.000828	8.89	647.73
	LLSM	2.285	8.569	0.241558	0.002558	7.59	453.15
	MLM	2.285	9.737	0.312489	0.001708	8.63	664.86
Dec	New method	2.89	11.59	0.017089	7.1E-05	10.33	969.50
	MoM	2.873	10.92	0.038829	0.000249	9.73	813.13
	EM	2.878	11.654	0.014747	8.36E-05	10.39	987.56
	EPFM	2.779	11.67	0.018847	7.07E-05	10.39	1008.77

	LLSM	2.686	10.09	0.151966	0.001182	8.97	663.92
	MLM	2.686	11.543	0.016029	7.17E-05	10.26	994.02

Table II: The Weibull parameters, average wind speeds and wind power densities for January to December 2019 for Stavenisse.

		k	c	Chi2	MSE	Vave	WPD
Jan	New method	2.245	6.752	0.0210582	7.784E-05	5.98	224.89
	MoM	2.12	6.381	0.032384	0.000104	5.65	199.65
	EM	2.141	6.854	0.023937	8.44E-05	6.07	245.17
	EPFM	2.127	6.854	0.024781	8.46E-05	6.07	246.66
	LLSM	1.986	6.062	0.063733	0.000214	5.37	182.74
	MLM	1.986	6.767	0.040823	0.000107	6.00	254.20
Feb	New method	2.352	4.838	0.26186	0.000778	4.29	79.75
	MoM	2.588	5.312	0.283359	0.001146	4.72	98.98
	EM	1.914	5.696	0.872909	0.002442	5.05	157.95
	EPFM	1.813	5.685	1.029193	0.002679	5.05	167.75
	LLSM	2.013	5.478	0.650232	0.001933	4.85	132.94
	MLM	2.013	5.777	0.796971	0.002371	5.12	155.92
Mar	New method	2.044	7.905	0.113338	0.001098	7.00	393.28
	MoM	2.588	8.053	0.201029	0.002168	7.15	344.86
	EM	1.996	8.645	0.211149	0.001082	7.66	527.18
	EPFM	2.016	8.646	0.199836	0.001102	7.66	521.88
	LLSM	1.864	6.996	0.144535	0.001344	6.21	301.97
	MLM	1.864	8.542	0.28148	0.000976	7.58	549.66
Apr	New method	2.84	5.71	0.031352	0.00014	5.09	116.90
	MoM	2.644	5.466	0.049075	0.00027	4.86	106.49
	EM	2.655	5.851	0.049488	0.000237	5.20	130.30
	EPFM	2.56	5.857	0.067415	0.000305	5.20	133.56
	LLSM	2.301	5.298	0.141539	0.000744	4.69	106.51
	MLM	2.301	5.733	0.148456	0.000598	5.08	134.96
May	New method	2.72	5.77	0.028218	0.000183	5.13	123.31
	MoM	2.588	5.373	0.057757	0.000386	4.77	102.43
	EM	2.6	5.755	0.031797	0.00023	5.11	125.52
	EPFM	2.568	5.757	0.034113	0.00025	5.11	126.59
	LLSM	2.266	4.865	0.194279	0.001439	4.31	83.49
	MLM	2.266	5.635	0.087851	0.00062	4.99	129.73
Jun	New method	2.545	5.103	0.040072	0.000105	4.53	88.66
	MoM	2.162	5.003	0.105115	0.000219	4.43	94.51
	EM	2.182	5.375	0.16661	0.000288	4.76	116.24
	EPFM	2.074	5.373	0.243978	0.000393	4.76	121.72
	LLSM	2.067	5.018	0.156067	0.000326	4.45	99.48

	MLM	2.067	5.331	0.232246	0.000382	4.72	119.28
Jul	New method	2.545	5.065	0.041105	0.000444	4.50	86.69
	MoM	2.467	4.811	0.057579	0.000445	4.27	75.81
	EM	2.482	5.16	0.045331	0.000514	4.58	93.16
	EPFM	2.441	5.162	0.04923	0.000534	4.58	94.32
	LLSM	2.305	4.434	0.139497	0.000906	3.93	62.35
	MLM	2.305	5.104	0.070237	0.000614	4.52	95.10
Aug	New method	2.472	5.631	0.049226	0.000308	4.99	121.40
	MoM	2.258	5.343	0.070015	0.000288	4.73	110.91
	EM	2.277	5.739	0.068958	0.000306	5.08	136.52
	EPFM	2.225	5.74	0.081248	0.000317	5.08	139.21
	LLSM	2.183	5.211	0.095321	0.00035	4.61	105.88
	MLM	2.183	5.707	0.090311	0.000323	5.05	139.09
Sep	New method	2.534	6.16	0.029031	0.000152	5.47	156.38
	MoM	2.398	5.857	0.042365	0.000275	5.19	139.52
	EM	2.414	6.284	0.039947	0.000166	5.57	171.49
	EPFM	2.375	6.286	0.045177	0.00018	5.57	173.68
	LLSM	2.081	5.598	0.10667	0.000632	4.96	137.21
	MLM	2.081	6.136	0.112397	0.000417	5.43	180.69
Oct	New method	2.73	6.352	0.01455	0.000106	5.65	164.19
	MoM	2.732	5.94	0.046373	0.000247	5.28	134.21
	EM	2.741	6.351	0.014714	0.00011	5.65	163.76
	EPFM	2.673	6.357	0.015238	8.91E-05	5.65	166.48
	LLSM	2.592	5.617	0.09611	0.000488	4.99	116.92
	MLM	2.592	6.302	0.020187	8.06E-05	5.60	165.12
Nov	New method	2.545	5.379	0.086794	0.000556	4.77	103.84
	MoM	2.285	5.243	0.13178	0.000514	4.64	103.80
	EM	2.341	5.628	0.114205	0.000679	4.99	125.99
	EPFM	2.298	5.63	0.12734	0.00069	4.99	127.95
	LLSM	2.433	4.993	0.127109	0.000491	4.43	85.55
	MLM	2.433	5.685	0.100811	0.000732	5.04	126.28
Dec	New method	2.415	6.714	0.089161	0.00035	5.95	209.10
	MoM	2.285	6.615	0.101157	0.000355	5.86	208.47
	EM	2.303	7.103	0.117586	0.000433	6.29	256.50
	EPFM	2.276	7.104	0.124374	0.000438	6.29	259.02
	LLSM	2.229	6.459	0.117744	0.000376	5.72	198.05
	MLM	2.229	7.074	0.134911	0.000441	6.27	260.18

Table III: WT specifications of different models

Model	Rated Power (kW)	Swept Area (m^2)	Number of Blades	Rated Speed (m/s)	Cut-in speed (m/s)

Skystream 3.7	2.1	10.87	3	11	3.2
Evance R9000	5	23.76	3	12	3
T701	1.5	7.1	3	11	-
Whisper 175	3.2	15.9	2	12	3.1

Table IV: Estimated W.P. at sites Europlatform using different W.T.s

Months	Estimated W.P. (W)			
	Skystream 3.7	Evance R9000	T701	Whisper 175
Jan	2667.806	5831.378	1742.541	3902.311
Feb	1731.178	3784.064	1130.76	2532.265
Mar	2303.372	5034.785	1504.502	3369.237
Apr	1330.105	2907.387	868.7899	1945.6
May	913.7197	1997.238	596.8178	1336.536
Jun	1103.854	2412.84	721.0084	1614.653
Jul	798.5822	1745.567	521.613	1168.119
Aug	1670.48	3651.389	1091.114	2443.48
Sep	2150.045	4699.638	1404.353	3144.96
Oct	2741.312	5992.05	1790.554	4009.831
Nov	2189.713	4786.346	1430.263	3202.984
Dec	3596.212	7860.718	2348.952	5260.329

Table V: Estimated W.P. at sites Stavenisse using different W.T.s

Months	Estimated W.P.			
	Skystream 3.7	Evance R9000	T701	Whisper 175
Jan	802.6635	1754.488	524.2788	1174.089
Feb	464.9777	1016.363	303.7113	680.1422
Mar	1307.336	2857.618	853.918	1912.295
Apr	467.8245	1022.586	305.5707	684.3063
May	464.9777	1016.363	303.7113	680.1422
Jun	374.918	819.5079	244.8866	548.4081
Jul	339.1989	741.432	221.5559	496.1603
Aug	473.5529	1035.107	309.3124	692.6855
Sep	628.908	1374.688	410.7863	919.9299
Oct	657.1166	1436.347	429.2114	961.1917
Nov	437.1423	955.52	285.53	639.4262
Dec	878.5242	1920.307	573.829	1285.054

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