

Highlights:

- The wind characteristics of seven locations in Jubail, Saudi Arabia.
- The wind speed data fitted to two-parameter Weibull distribution function.
- Estimation of Weibull parameters by maximum likelihood, least-squares regression method (LSRM), and WASP algorithm.
- The most probable and maximum energy carrying wind speed based on Weibull scale and shape parameters at all sites.
- Maximum likelihood method represents the wind data most accurately.
- The energy output from a 3 MW wind machine was 11,136 MWh/yr with a plant capacity factor (PCF) of 41.3%.

Wind power characteristics of seven data collection sites in Jubail, Saudi Arabia using Weibull parameters

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Abstract:

The wind characteristics of seven locations in Jubail, Saudi Arabia were analysed by using five years of wind data of six sites and three years data of one site at 10 m above ground level (AGL). The highest annual mean wind speed of 4.52 m/s was observed at Industrial area (east) and lowest of 2.52 m/s at Pearl beach. The wind speed data at all seven sites were fitted to two-parameter Weibull distribution function. Weibull parameters were estimated using maximum likelihood, least-squares regression method (LSRM), and WAsP algorithm. The most probable and maximum energy carrying wind speed were estimated based on Weibull scale and shape parameters found by all three methods. All methods were found to represent the wind data at all the sites in Jubail, accurately. The correlation coefficient showed that the maximum likelihood method represents the wind data slightly better than other two methods. The wind power output from five commercially available wind machines of rated power ranging from 1.8 - 3.3 MW showed that Jubail industrial area (east) is most promising. The energy output from a 3 MW wind machine at this site was found to be 11,136 MWh/yr with a plant capacity factor (PCF) of 41.3%.

Keywords: Wind power; Weibull parameters; maximum energy carrying wind speed; most probable wind speed; plant capacity factor.

1. Introduction

The term green energy is used for those sources of energy which do not produce any of the harmful greenhouse gases. Further, the cleanest sources of energy are those which utilise the natural flows of the earth. These sources are known as renewable sources of energy and they will never die out unlike fixed reserves of fossil and nuclear fuels which emits greenhouse gases. Wind energy is one of the promising sources of renewable energy and is getting worldwide recognition due to its competitive cost of production compared with traditional means.

Wind speed frequency distribution is an important statistical tool in predicting the wind energy output at a particular location [1]. The Weibull distribution function is found to represent the variable nature of wind speed better than other distributions in most of the locations worldwide [2, 3, 4, 5]. The Weibull function is a two-parameter function, namely, shape parameter, k and scale parameter, c . There are several methods available in the literature for the determination of these two parameters. Stevens and Smulders [6] found the values of k and c by five different estimation methods namely, method of moments, method of energy pattern factor, maximum likelihood method, Weibull probability paper method and percentile estimators. Almost same values were obtained by all five methods.

Seguro and Lambert [7] calculated the Weibull parameters using maximum likelihood method, graphical method and modified maximum likelihood method. It was reported that when wind speed data is available in time-series format, the maximum likelihood method is the recommended method for estimating the parameters. When wind speed data is available in frequency distribution format, the modified maximum likelihood method is the recommended method. The graphical method is reported to be the least accurate. Bagiorgas et al. [8] calculated the Weibull parameters using the wind data

from seven different sites in Saudi Arabia. The parameter estimation methods used were least-squares regression method, method of moments, alternative maximum likelihood estimation method, maximum likelihood method, and WAsP Algorithm. The calculated values using the five different methods were found to be in good agreement at all the measurement heights. The correlation between the monthly mean values of Weibull scale parameter and the measured wind speed values was found to be linear at all the sites.

Rocha et al. [9] compared seven numerical methods for determining the Weibull parameters at northeast region of Brazil. The estimation methods were graphical method, maximum likelihood method, energy pattern factor method, moment method, empirical method, modified maximum likelihood method, and equivalent energy method. The equivalent energy method was found to be an efficient for determining the k and c parameters to fit Weibull distribution curves for wind speed data. Akdag and Dinler [10] developed a new method called power density method for estimation of Weibull parameters. This new method was compared with graphic, maximum likelihood and moment methods and it was concluded that power density method is suitable and efficient for Weibull parameters estimation.

Wind speed assessment of six sites in the island of Crete, Greece was done [11]. The effect of topographical features on wind characteristics was studied. The Weibull, Rayleigh, Lognormal, Gamma, and Inverse Gaussian distributions probability distributions were examined for their ability to model the wind speed frequency distributions. The most efficient methods for the estimation of the distribution parameters were found to be moments method, maximum likelihood method, and least-squares method.

For wind resource assessment of Selcuk University campus in Turkey, one year wind data at three different heights was analysed [12]. Energy output from a 6 MW installed capacity wind farm composed of 1.0, 1.5, and 2.0 MW rated power wind turbines was

calculated and reported by Faruk et al. [12]. The minimum basic payback period was found to be 6.44 years.

Onea et al. [13] presented the wind resource assessment of north-western side of the Black Sea using measured wind speed data over a period of 11 years. The analysis indicated that the Romanian coastal region has more wind energy potential during the winter season, with an average annual wind speed of about 9.7 m/s at 80 m and a power density of 870 W/m². This study concluded that the north-western side of the Black Sea is a promising site for the wind farm development.

2. Sites, equipment and data description

In 1933, geologists explored oil in Jubail, Saudi Arabia. In 1983, the largest engineering and construction project ever was started at Jubail industrial city. Presently, Jubail industrial city is host to more than 160 industrial enterprises and home to almost 70,000 full-time residents. The Jubail infrastructure has the capability to operate continuously without failure of power in any of the existing facilities while meeting community requirements within high modern living standards where all the necessities of life and tourism and recreation are available.

To study the viability of wind power generation for the Jubail city, the historical wind data from seven weather stations was obtained from the Environment and Control Department (Royal commission for Jubail). The locations of these sites are shown in Fig. 1. The photos of the wind towers at Industrial area (central), Al Bahar desalination plant, Pearl beach and Al-Reggah district are shown in Fig. 2, 3, 4 and 5 respectively. All the seven sites are located within a radius of 20 kms. The availability of long term wind speed data or an accurate forecasting method for missing data is very important in identifying suitable locations for wind turbines [14]. This governmental organisation is responsible for the maintenance, calibration and collection of meteorological data at Jubail Industrial city. The latitude/longitude and UTM coordinates of the weather station are given in Table. 1. The specifications of the wind speed sensors installed on

the wind tower are given in Table 2. The list of weather parameters recorded is given in Table 3. The description of the terrain in the vicinity of all the sites is given in Table 4.

The coastal city of Jubail also hosts a water desalination plant, Saline water conversion corporation, SWCC. This plant produces 363.4 million cubic meters of water per annum supplying it to national capital, Riyadh and Jubail. The desalination in this plant is done by conventional means and out of all the alternatives of renewable energy desalination wind powered desalination can be considered most promising [15].

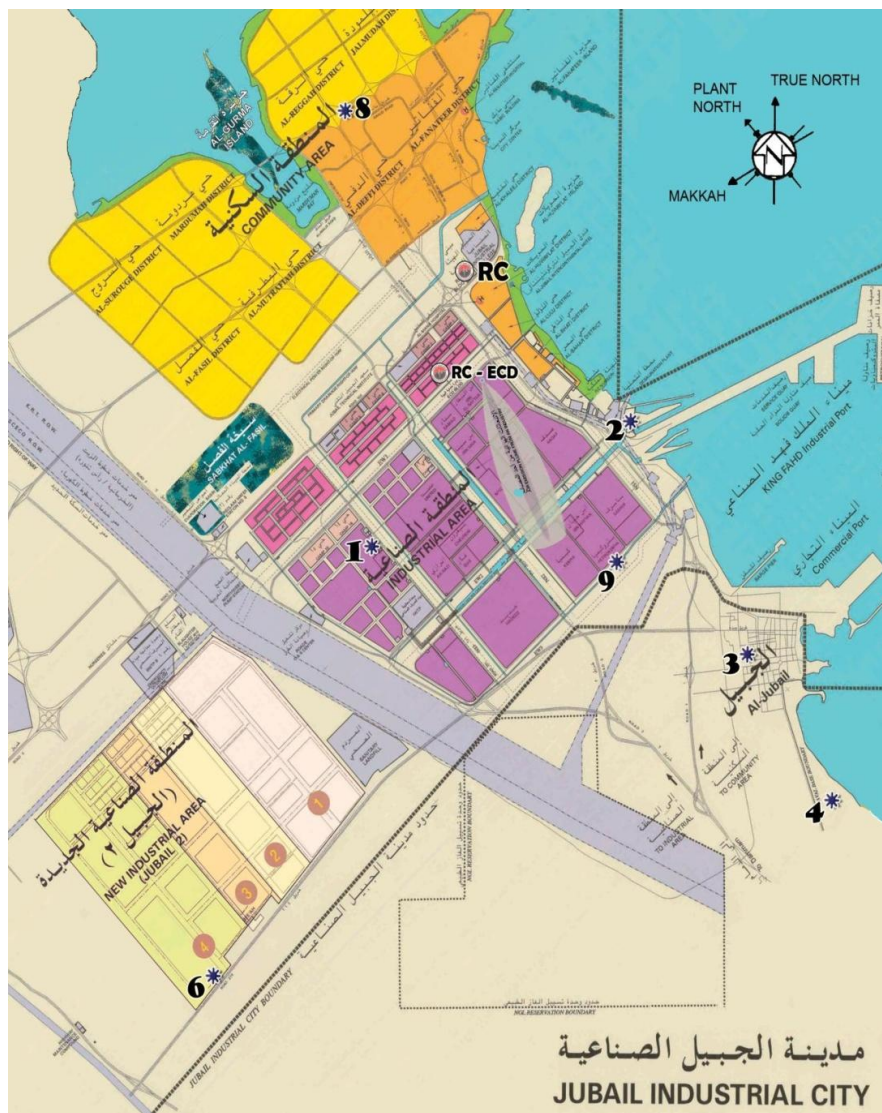


Fig. 1. Weather stations in Jubail industrial city

Table 1

Latitude/longitude and UTM coordinates of weather data collection sites.

	Site name	Degrees, Minutes, Seconds	Degrees	Minutes	Seconds	UTM
Site 1	Industrial area (Central)	27° 2'15.76"N	27°	2	15.76	2,991,457.88
		49°32'2.56"E	49°	32	2.56	354,594.12
Site 2	Al-Bahar desalination plant	27° 4'27.49"N	27°	4	27.49	2,995,436.09
		49°36'3.24"E	49°	36	3.24	361,271.25
Site 3	Pearl beach	27° 0'36.85"N	27°	0	36.85	2,988,282.92
		49°39'9.56"E	49°	39	9.56	366,327.78
Site 4	Naval Base	26°55'39.92"N	26°	55	39.92	2,979,084.69
		49°42'42.89"E	49°	42	42.89	372,114.33
Site 6	Industrial area 2 (South)	26°55'13.40"N	26°	55	13.40	2,978,520.20
		49°29'0.10"E	49°	29	0.1	349,410.12
Site 8	Al-Reggah District	27° 7'54.03"N	27°	7	54.03	3,001,869.16
		49°31'57.02"E	49°	31	57.02	354,562.88
Site 9	Industrial area (East)	27° 1'49.95"N	27°	1	49.95	2,990,576.71
		49°36'41.14"E	49°	36	41.14	362,261.81

Table 2

Specifications of the wind speed sensor at data collection site.

PERFORMANCE CHARACTERISTICS	
Maximum Operating Range:	0 - 125 mph (0 - 60 m/s)
Starting Speed:	0.5 mph (0.22 m/s)
Calibrated Range:	0 - 100 mph (0 - 50 m/s)
Accuracy:	±1% or 0.15 mph (0.07 m/s)
Resolution:	<0.1 mph or m/s
Temperature Range:	-50°C to +65°C (-58°F to +149°F)
Distance Constant:	less than 5 ft (1.5m) of flow (meets EPA specifications)
ELECTRICAL CHARACTERISTICS	
Power Requirements:	12 VDC at 10 mA, 12 VDC at 350 mA for internal heater
Output Signal:	11 volt (pulse frequency equivalent to speed)
Output Impedance:	100 Ω maximum
PHYSICAL CHARACTERISTICS	
Weight:	1.5 lbs (.68 kg)
Finish:	Clear anodised aluminium; Lexan cup assembly.
CABLE & MOUNTING	
PN 1953 Mounting:	Cable Assembly; specify length in feet or metres PN 191 Crossarm Assembly

Table 3

Parameter list of the weather data collection tower.

Sr.No	Parameter Code	Description	Unit
1	ATM	Atmospheric Temperature	DegC
2	PRE	Precipitation	mm
4	RH	Relative Humidity	%
6	VWD10	Vector Wind Direction 10m	deg
9	VWS10	Vector Wind Speed 10m	m/s



Fig. 2. Wind tower at Industrial area (Central)



Fig. 3. Wind tower at Al-Bahar desalination plant



Fig. 4. Wind tower at Pearl beach



Fig. 5. Wind tower at Al-Reggah district

Table 4

Description of the terrain in the vicinity of weather stations.

Site	Description
Industrial area (Central)	Only station where weather data is available at three heights AGL. Surrounded mainly by plain terrain with some warehouses of 8 - 10 m height about 200 m away in west direction.
Al-Bahar desalination plant	Located on sea shore near desalination plant. Terrain is mostly plain and surrounded by very small shrubs.
Pearl beach	Located in Jubail residential area and surrounded by 3-4 story buildings. This station recorded minimum wind speed out of all weather stations.
Naval Base	Located near Dhahran-Jubail highway. Terrain is mostly plain and surrounded by very small shrubs and few residential buildings 200 m away towards east.
Industrial area 2 (South)	Surrounded mainly by plain terrain with some warehouses of 8 - 10 m height about 300 m away in west and north direction.
Al-Reggah District	Location mostly surrounded by shrubs. Surrounding clear with a 3 story building around 150 m away in north-eastern direction.
Industrial area	Surrounded mainly by plain terrain with some warehouses of 8 - 10 m height

(East)	about 150 m away in north - west direction
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3. Results and Discussion

This study presents the analysis of wind speed data from seven different sites at Jubail city in Saudi Arabia at 10 m height above ground level (AGL). The wind data is collected over a period of 5 years (2008 - 2012) for all sites except the site at Naval base where the data was available only for 3 years (2010 - 2012).

3.1 Statistics of Mean Wind Speed

The hourly average wind speed values over entire period of data collection for all the seven sites at 10 m height are presented in Table 5. The highest annual mean wind speed of 4.53 m/s was observed at Industrial area (East) and the lowest of 2.25 m/s at Pearl beach. The monthly (max., daily high, mean, daily low, and min.) wind speed at all sites are shown in Fig. 6. It was observed that the highest monthly mean wind speed was occurred in February/June and the lowest in September/October at all sites. The wind rose plots of all seven sites are shown in Fig. 7. The hourly values of wind direction and wind speed are presented in these wind rose plots. It can be observed from these plots that the most prevailing wind direction at all sites was from the north-west.

Table 5
Wind speed statistics of all sites.

Station	Mean	Maximum	Standard Deviation
Industrial area (Central)	3.27	11.90	1.985
Al-Bahar desalination plant	3.74	2.40	2.193
Pearl beach	2.26	8.70	1.109
Naval Base	3.78	13.80	2.220
Industrial area 2 (South)	4.31	27.00	2.983
Al-Reggah District	2.91	13.60	1.511
Industrial area (East)	4.53	19.30	2.520

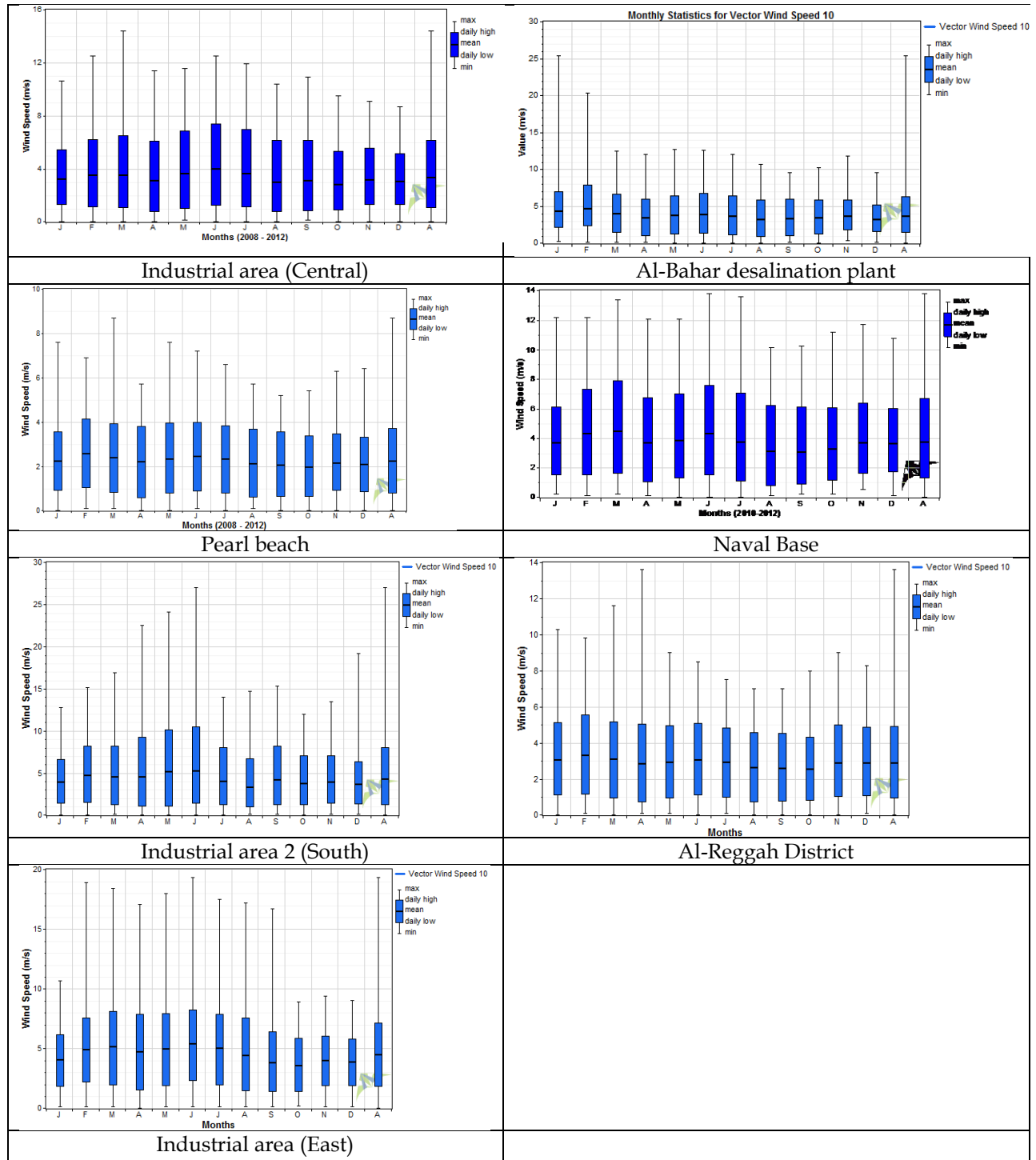
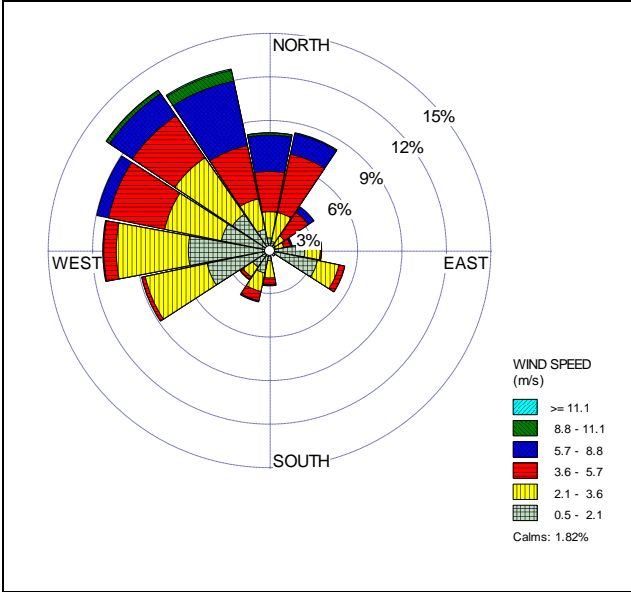
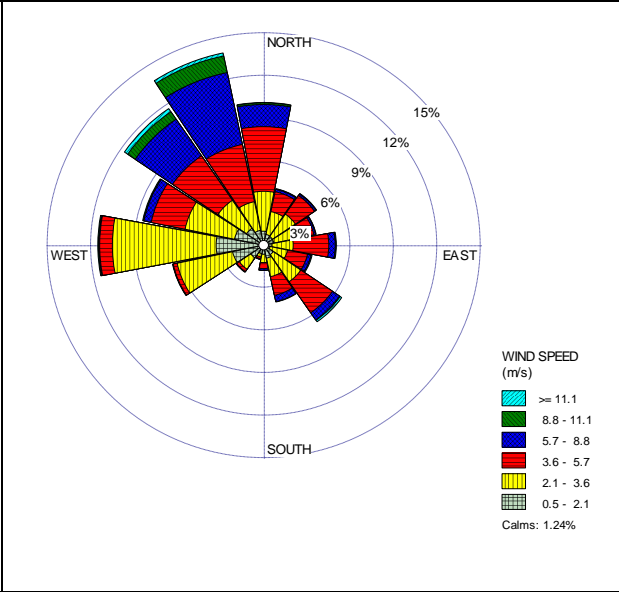


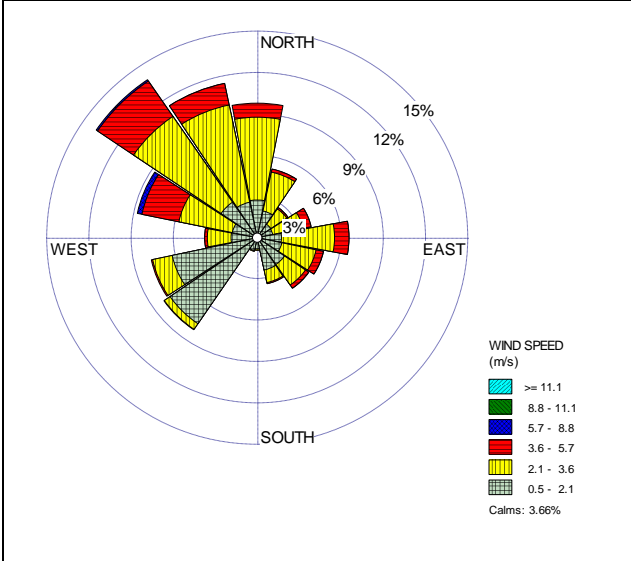
Fig. 6. Monthly maximum, daily high, daily mean, daily low, and minimum wind speed at all sites.



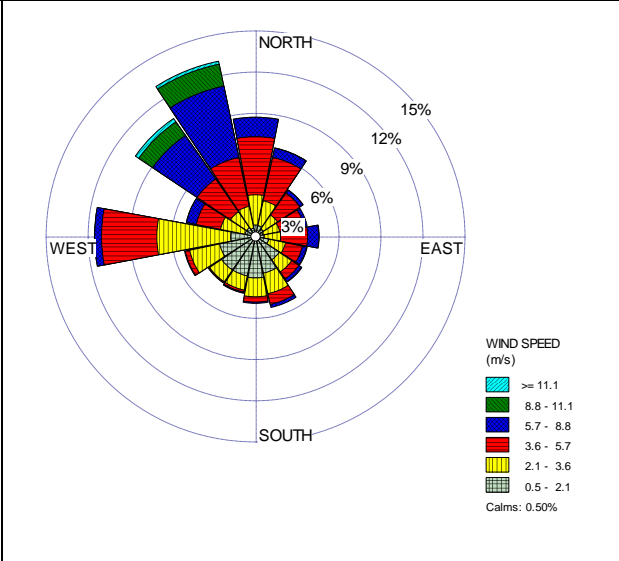
Industrial area (Central)



Al-Bahar desalination plant



Pearl beach



Naval Base

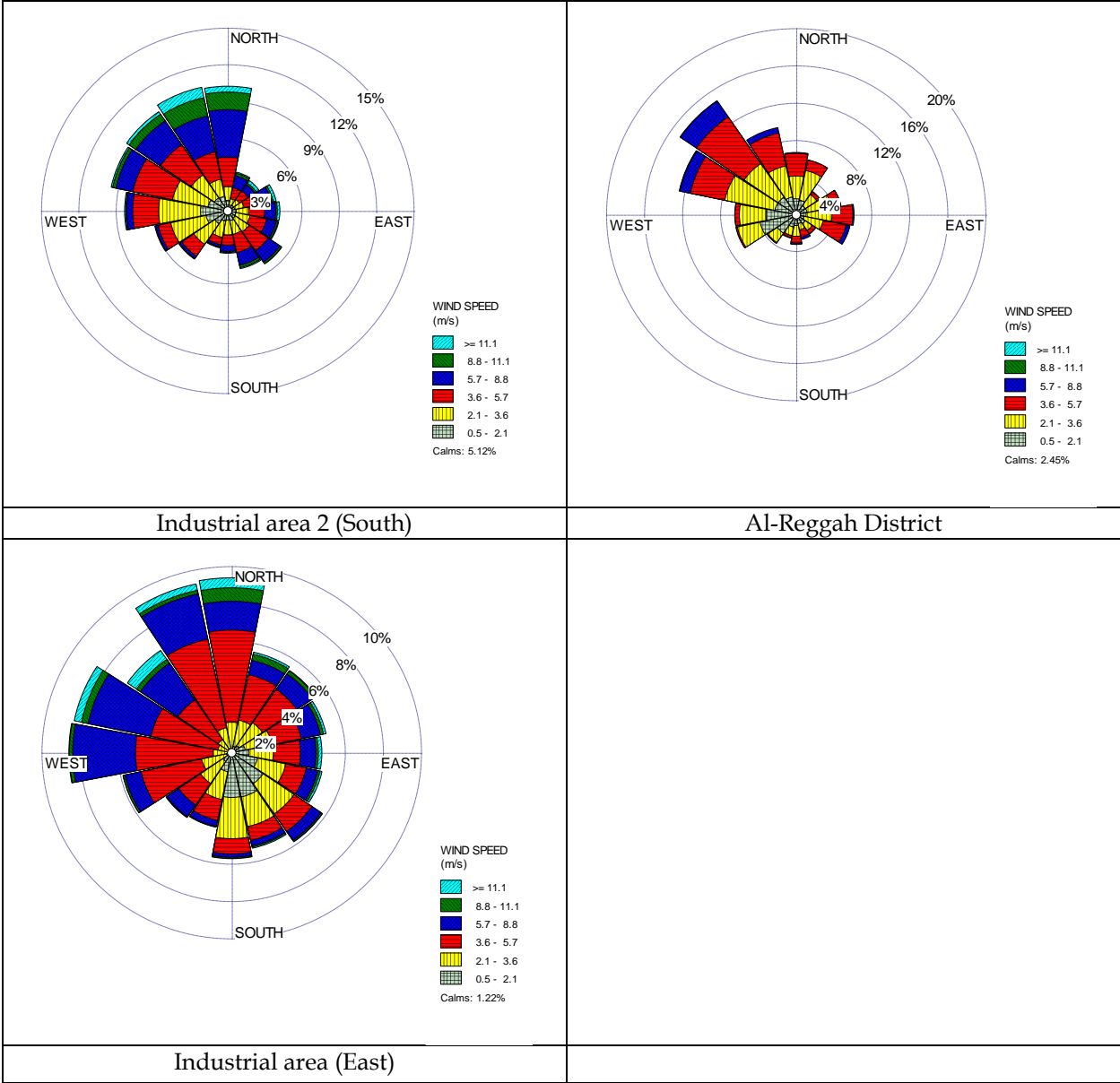


Fig. 7. Wind rose plots at 10 m AGL at all sites

3.2 Weibull Distribution

The two-parameter Weibull distribution is frequently used to characterise wind behaviour because it provides a good representation of wind data [2, 3, 4, 5]. This distribution function shows the probability of the wind speed in a 1 m/s bins centered on a particular wind data time series. The Weibull distribution function is expressed as [16]:

$$P(v) = \frac{k}{c} \left(\frac{v}{c}\right)^{k-1} \exp\left\{-\left(\frac{v}{c}\right)^k\right\}, \quad (1)$$

where $P(v)$ is the frequency of incidence of wind speed, v . The scale factor, c in m/s, is indicative of mean wind speed and k is the dimensionless shape factor, which describes the shape and width of the distribution. The Weibull distribution is therefore determined by the parameters, c and k . The cumulative Weibull distribution, $P_{(v)}$, which gives the probability of the wind speed greater than the value, v , is expressed as:

$$P_{(v)} = \exp\left\{-\left(\frac{v}{c}\right)^k\right\}, \quad (2)$$

There are several methods to estimate Weibull parameters. Three methods commonly used are discussed in this study.

3.2.1 Maximum Likelihood Method

Maximum likelihood method was suggested by Stevens and Smulders [6]. This method requires extensive iterative calculations. Shape and scale parameters of Weibull distribution are estimated by these two equations

$$k = \left(\frac{\sum_{i=1}^n \frac{v_i^k \ln(v_i)}{v_i^k} - \frac{\sum_{i=1}^n \ln(v_i)}{n}}{\sum_{i=1}^n \frac{1}{v_i^k}} \right)^{-1} \quad (3)$$

$$c = \left(\frac{\sum_{i=1}^n (v_i)^k}{n} \right)^{\frac{1}{k}} \quad (4)$$

where v_i is the wind speed and n is the number of nonzero wind speeds. This method is implemented by taking care of zero wind speeds which make logarithm indefinite and then calculate shape parameter. The scale parameter is found using a numerical technique in order to find the root of Eq. (3) around $k = 2$.

3.2.2 Least-Squares Regression Method (LSRM)

The equation of the probability density function, after a double logarithmic transformation, can be written as follows:

$$\ln[-\ln(1 - F(v))] = k \ln(c) \quad (5)$$

The above equation is linear and can be fitted using the LSRM [17]. The cumulative distribution function $F(v)$ can be estimated easily, using an estimator, which is the median rank.

3.2.3 WAsP Algorithm

There are two requirements of WAsP algorithm

- (1) The power density of the fitted Weibull distribution is equal to that of the observed distribution and
- (2) The proportion of values above the mean is the same for the fitted Weibull distribution as for the observed distribution.

Let X represents the proportion of the observed wind speeds that exceed the mean wind speed. The cumulative distribution function $F(U)$ gives the proportion of values that are less than U , so $1-F(U)$ is the proportion of values that exceed U . One can therefore write the second requirement as follows:

$$X = 1 - F(\bar{U}) \quad (6)$$

Since the mean wind speed is given by the following equation:

$$\bar{U} = c\Gamma\left(\frac{1}{k} + 1\right) \quad (7)$$

Substitute the aforementioned mean value in the expression of the cumulative distribution function to get second requirement:

$$X = \exp\left[-\Gamma\left(\frac{1}{k} + 1\right)^k\right] \quad (8)$$

Taking the natural logarithm of both sides gives

$$-\ln X = \Gamma\left(\frac{1}{k} + 1\right)^k \quad (9)$$

In performing the WAsP algorithm to fit the Weibull distribution, WindoGrapher [18] software (<http://www.mistaya.ca/>) calculates X and then solves the above equation iteratively by using the Brent method, in order to find the k parameter. Requirement (1) allows us to calculate the c parameter. On the basis of the Weibull distribution, the mean WPD, assuming constant air density, is calculated as follows:

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

We can also write an equation for the mean power density of the observed wind speeds as follows:

$$WPD = \frac{1}{2N} \rho \sum_N U_i^3 \quad (11)$$

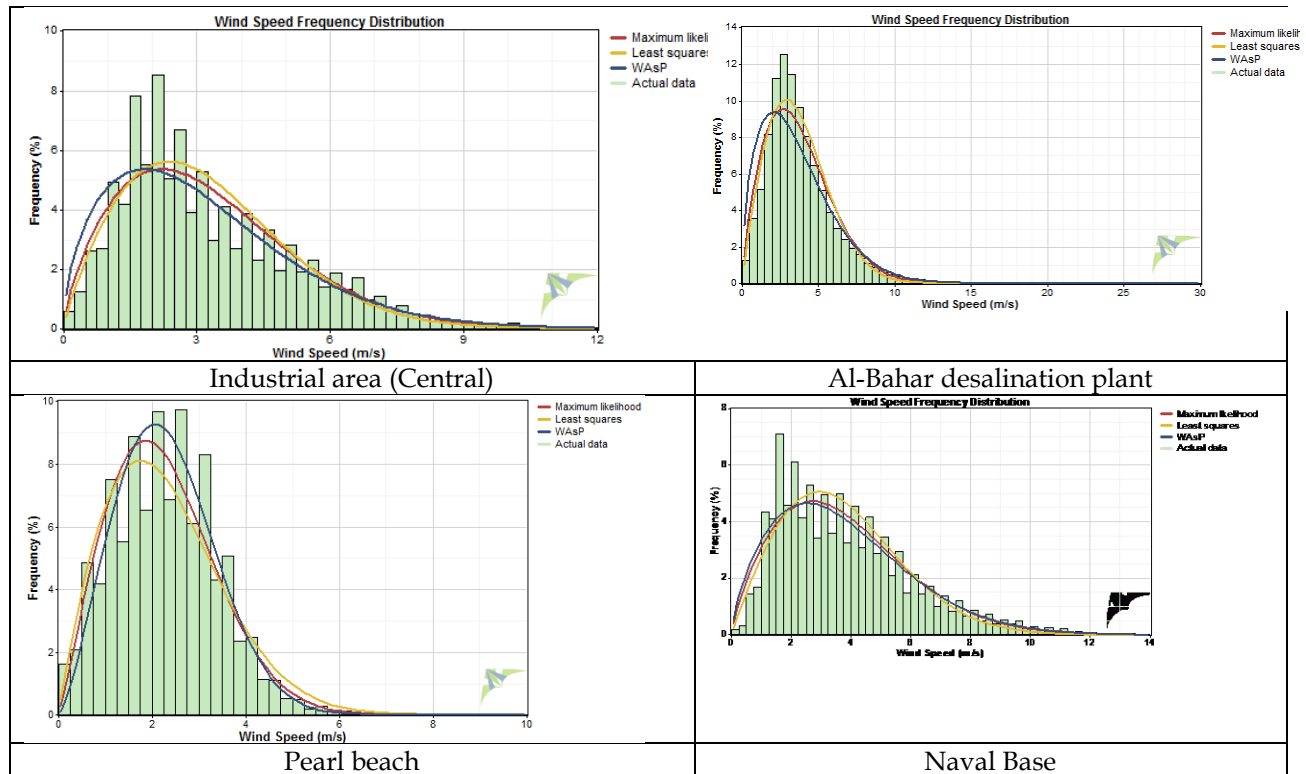
As per requirement (1), these must be equal, so one can write,

$$c^3 \Gamma \left(\frac{3}{k} + 1 \right) = \frac{1}{N} \sum_N U_i^3 \quad (12)$$

Solving this for c gives us the following:

$$c = \sqrt[3]{\frac{\sum_N U_i^3}{N \Gamma \left(\frac{3}{k} + 1 \right)}} \quad (13)$$

For each station, the WindoGrapher software was used to estimate the mean monthly and annual values of Weibull parameters for the entire period of measurements. The wind speed frequency distribution at all seven sites is shown in Fig. 8 below. The actual wind data and Weibull fitting curves (maximum likelihood method, least squares regression methods and WAsP method) are also shown in Fig. 8.



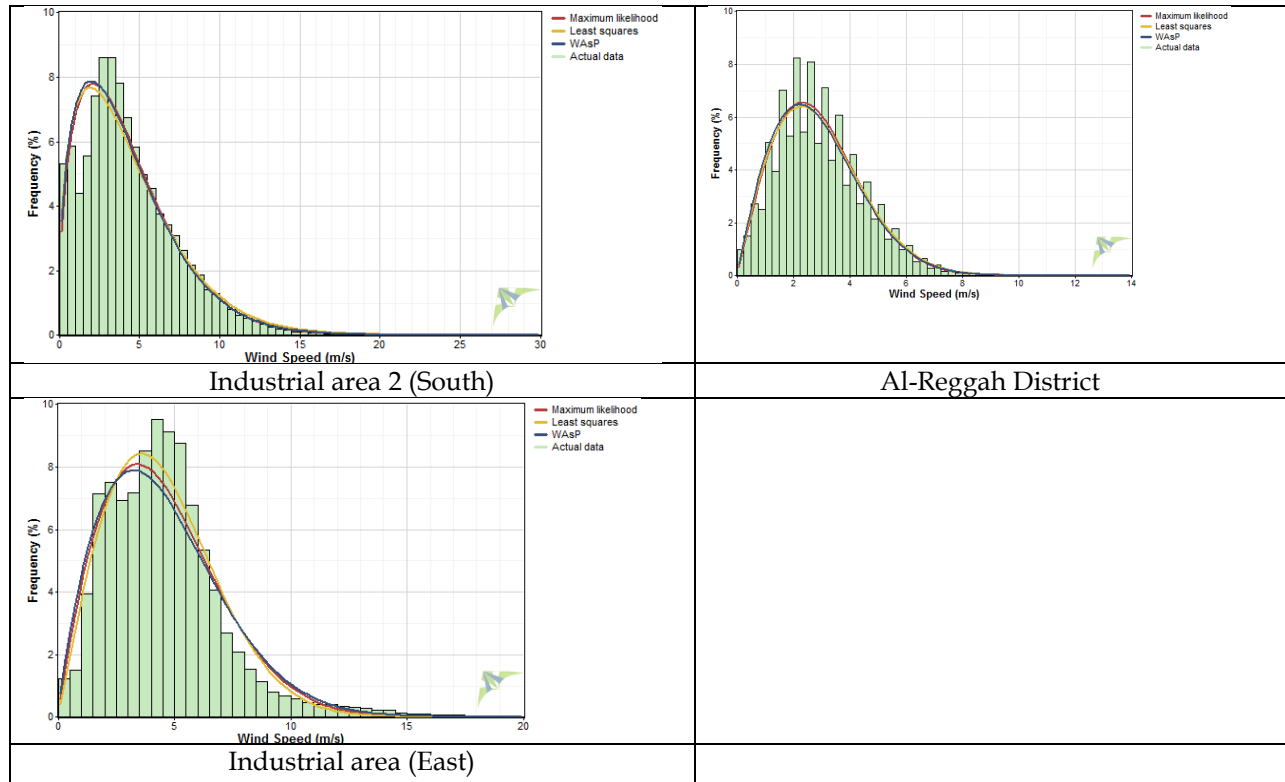


Fig. 8. Weibull probability distributions (three methods) and actual data at all sites.

The Weibull parameters, wind power density and coefficient of determination, R^2 for all the three estimation methods are given in Table 6. The R^2 is a measure of how well data points fit a specified curve. It can be observed that the values of R^2 for all three estimation methods are quite close. However, maximum likelihood method is found to be the best method to represent the wind data in Jubail followed by least square regression method and WAsP. The monthly and annual Weibull parameters obtained by maximum likelihood method are given in Table 7 and 8 respectively. The monthly and annual variation of Weibull parameters k and c is shown in Figs. 9, 10, 11 and 12.

Table 6
Weibull parameters at all sites from three different estimation methods.

Site	Maximum Likelihood				Least Squares				WAsP			
	Weibull		Power Density (W/m ²)	R ²	Weibull		Power Density (W/m ²)	R ²	Weibull		Power Density (W/m ²)	R ²
	K	c (m/s)			K	c (m/s)			K	c (m/s)		
Industrial area (Central)	1.724	3.675	48.5	0.86	1.845	3.640	43.1	0.85	1.563	3.519	49.6	0.85
Al-Bahar desalination plant	1.800	4.218	69.2	0.95	1.952	4.200	61.9	0.96	1.548	4.012	74.8	0.91
Pearl beach	2.104	2.539	12.7	0.91	1.924	2.582	14.6	0.90	2.367	2.611	12.5	0.91
Naval Base	1.799	4.263	71.4	0.86	1.973	4.205	61.4	0.85	1.718	4.218	73.7	0.86
Industrial area 2 (South)	1.450	4.740	139.2	0.92	1.392	4.788	155.9	0.92	1.421	4.678	139.4	0.92
Al-Reggah District	2.008	3.286	28.8	0.94	1.957	3.304	30.1	0.93	1.938	3.242	28.7	0.93
Industrial area (East)	1.876	5.098	116.0	0.94	1.999	5.096	107.8	0.95	1.799	5.100	122.3	0.93

Table 7
Monthly Weibull parameters at all sites (Maximum likelihood method)

Location	Industrial area (Central)		Al-Bahar desalination plant		Pearl beach		Naval Base		Industrial area 2 (South)		Al-Reggah District		Industrial area (East)	
	k	c	k	c	k	c	k	c	k	c	k	c	k	c
Jan	1.892	3.691	1.572	4.869	2.016	2.539	2.013	4.202	1.666	4.443	1.845	3.467	2.415	4.591
Feb	1.680	3.962	1.697	5.254	2.126	2.913	1.88	4.913	1.556	5.247	1.893	3.760	1.942	5.579
Mar	1.700	4.003	1.835	4.556	2.108	2.698	1.73	5.053	1.566	5.058	1.942	3.483	1.91	5.817
Apr	1.649	3.504	1.871	3.938	2.118	2.509	1.896	4.203	1.528	5.117	2.045	3.246	1.938	5.363
May	1.662	4.106	1.759	4.247	2.253	2.644	1.825	4.409	1.382	5.662	2.178	3.314	1.909	5.644
Jun	1.673	4.476	1.731	4.442	2.047	2.785	1.704	4.876	1.351	5.800	2.063	3.484	1.721	6.133
Jul	1.675	4.133	1.885	4.159	2.307	2.651	1.692	4.279	1.266	4.378	2.259	3.313	1.940	5.706
Aug	1.608	3.392	2.035	3.724	2.267	2.406	1.787	3.556	1.356	3.686	2.229	2.966	1.938	5.060
Sep	1.762	3.533	2.033	3.802	2.256	2.343	1.888	3.543	1.643	4.753	2.165	2.95	1.473	4.244
Oct	1.759	3.189	2.044	3.941	2.118	2.229	1.821	3.755	1.697	4.237	2.127	2.883	2.410	4.095
Nov	2.056	3.639	2.169	4.180	2.258	2.436	2.101	4.237	1.625	4.436	2.024	3.290	2.699	4.516
Dec	2.020	3.492	2.231	3.643	1.989	2.355	2.009	4.191	1.461	4.101	1.912	3.282	2.535	4.380

Table 8
Annual Weibull parameters at all sites (Maximum likelihood method)

Year	Industrial area (Central)		Al-Bahar desalination plant		Pearl beach		Naval Base		Industrial area 2 (South)		Al-Reggah District		Industrial area (East)	
	k	c	k	c	k	c	k	c	k	c	k	c	k	c
2008	1.714	3.971	1.603	4.777	2.128	2.667	-	-	1.989	5.480	1.941	3.363	2.434	4.757
2009	1.700	3.658	1.899	4.301	2.109	2.548	-	-	1.875	5.251	1.992	3.318	2.318	4.450
2010	1.701	3.611	1.913	4.163	2.111	2.443	1.811	4.151	1.660	4.338	1.996	3.141	2.457	4.671
2011	1.743	3.880	1.927	3.641	2.178	2.578	1.834	4.429	1.194	3.849	2.104	3.343	2.320	4.563
2012	1.724	3.675	1.987	4.229	2.057	2.467	1.763	4.212	1.096	4.685	2.025	3.261	1.876	5.098

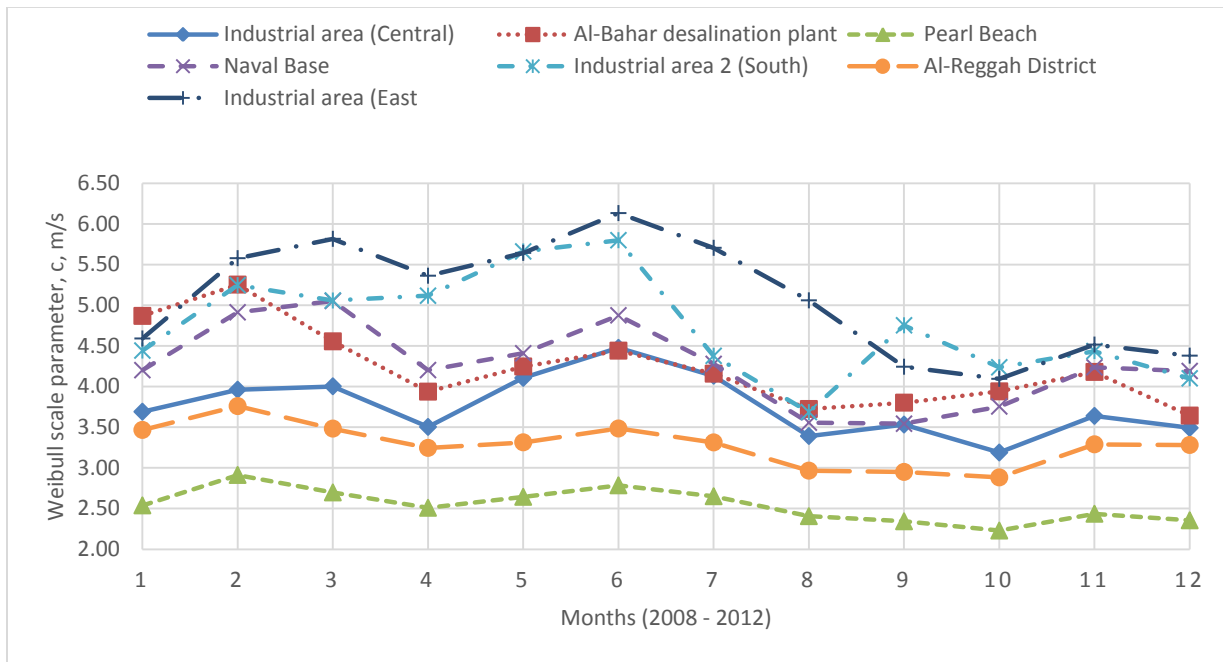


Fig. 9. Monthly variation of Weibull scale parameter, c , m/s at all sites.

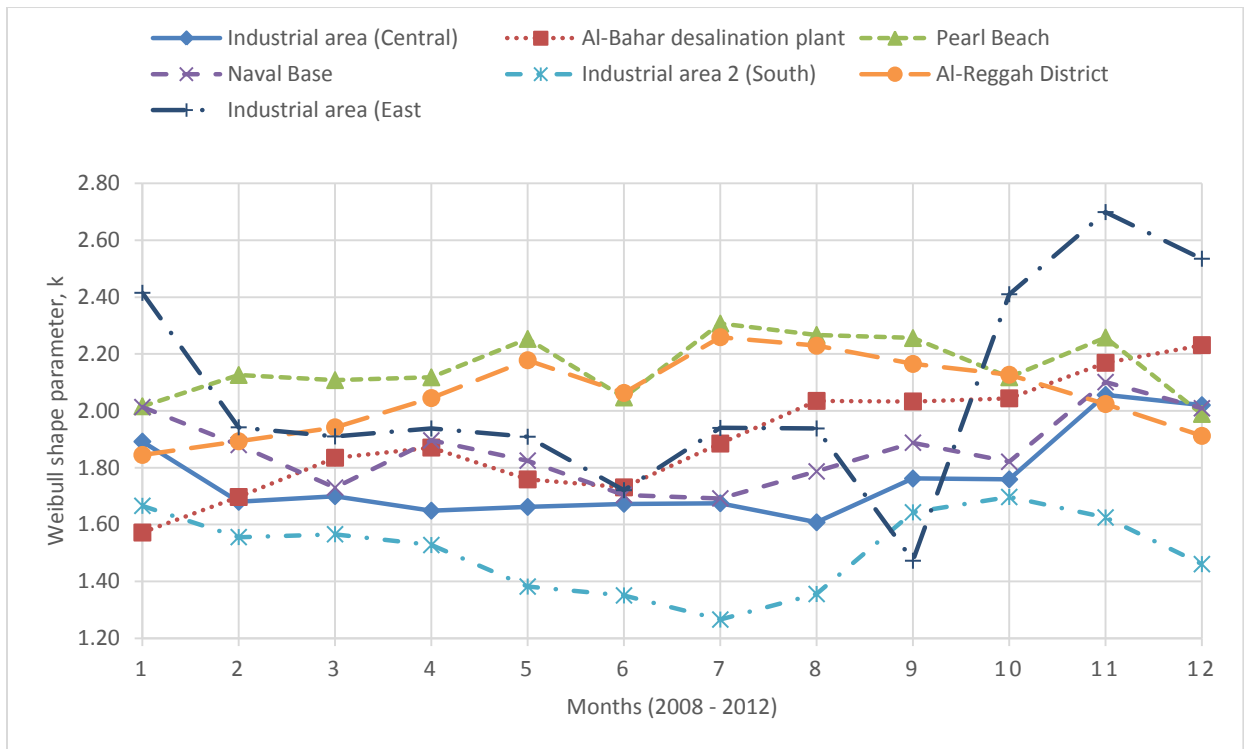


Fig. 10. Monthly variation of Weibull shape parameter, k at all sites.

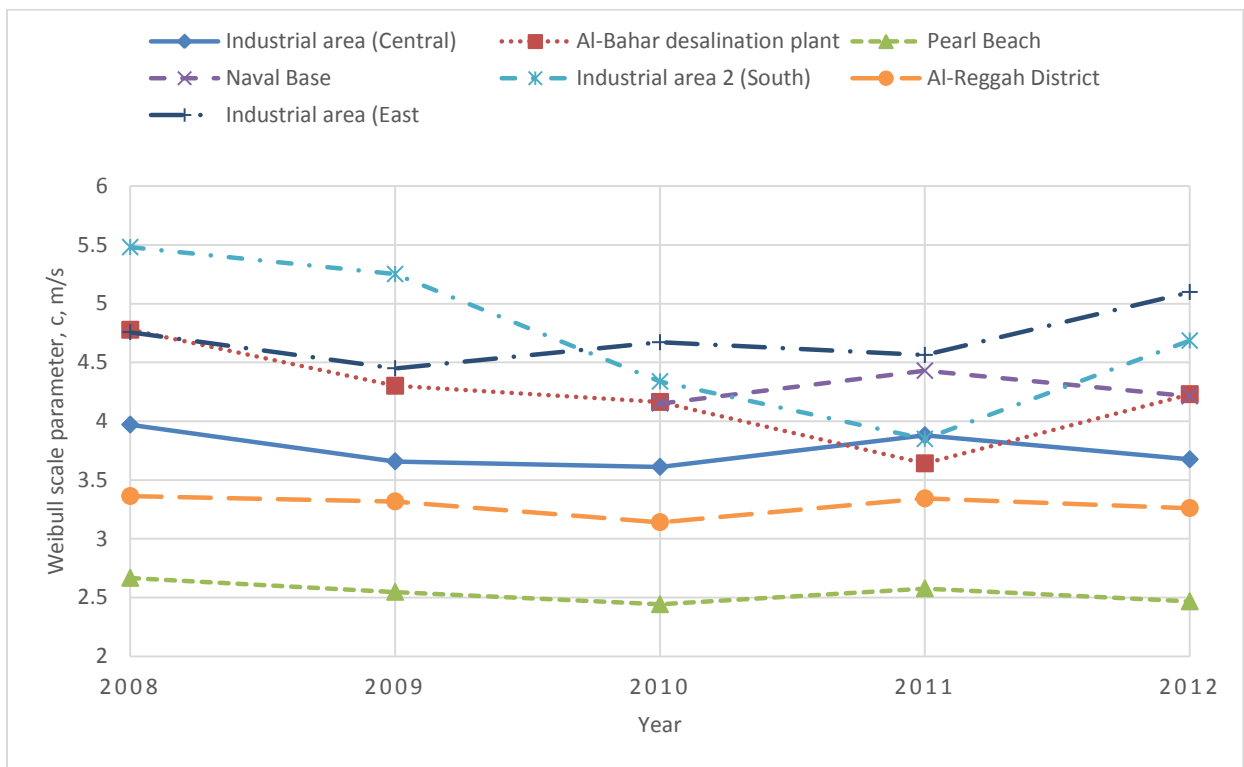


Fig. 11. Annual variation of Weibull scale parameter, c , m/s at all sites.

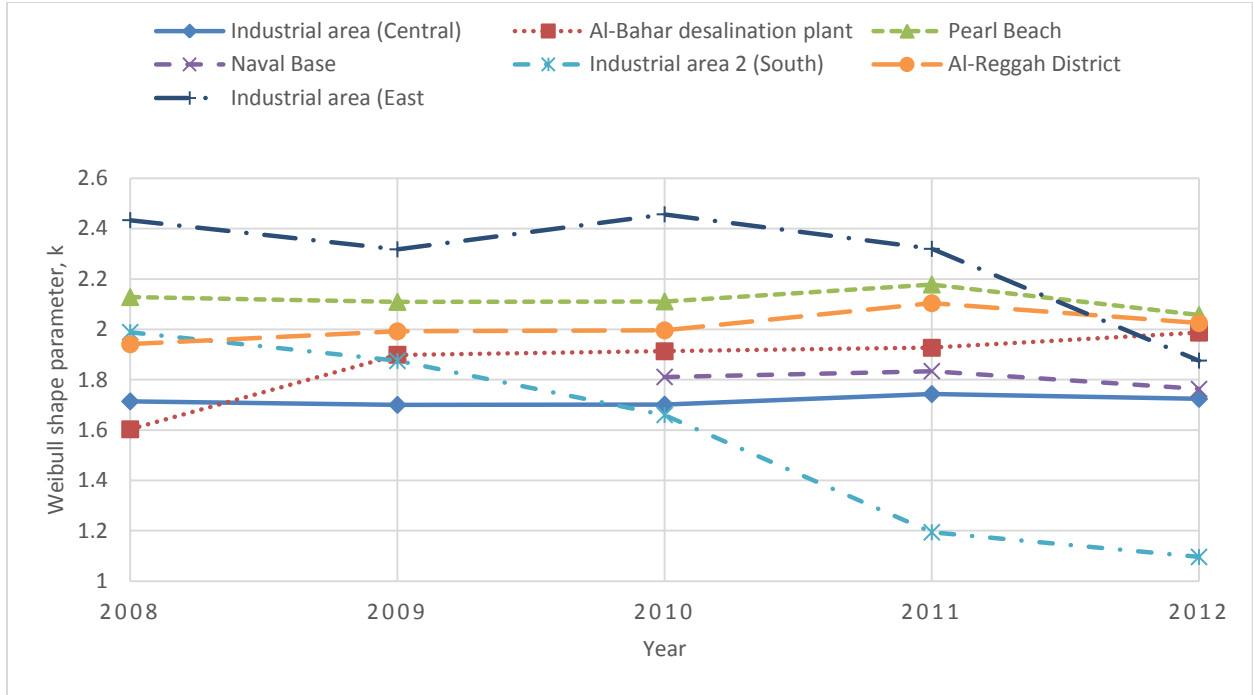


Fig. 12. Annual variation of Weibull shape parameter, k at all sites.

3.3 Most Probable Wind Speed

The most probable wind speed simply provides the most frequently occurring wind speed for a given wind probability distribution. The most probable wind speed can be calculated using the Weibull shape and scale parameters via the following equation [19]:

$$V_{mp} = c \left(1 - \frac{1}{k}\right)^{\frac{1}{k}} \quad (14)$$

The most probable wind speed at all the seven locations at 10 m AGL was found using all three estimation methods and is shown in Fig. 13. The values at each site are in close agreement. The highest most probable wind speeds determined by maximum likelihood method, least-square regression methods and WAsP are 3.39, 3.6 and 3.24 m/s respectively and were observed at Industrial area (east).

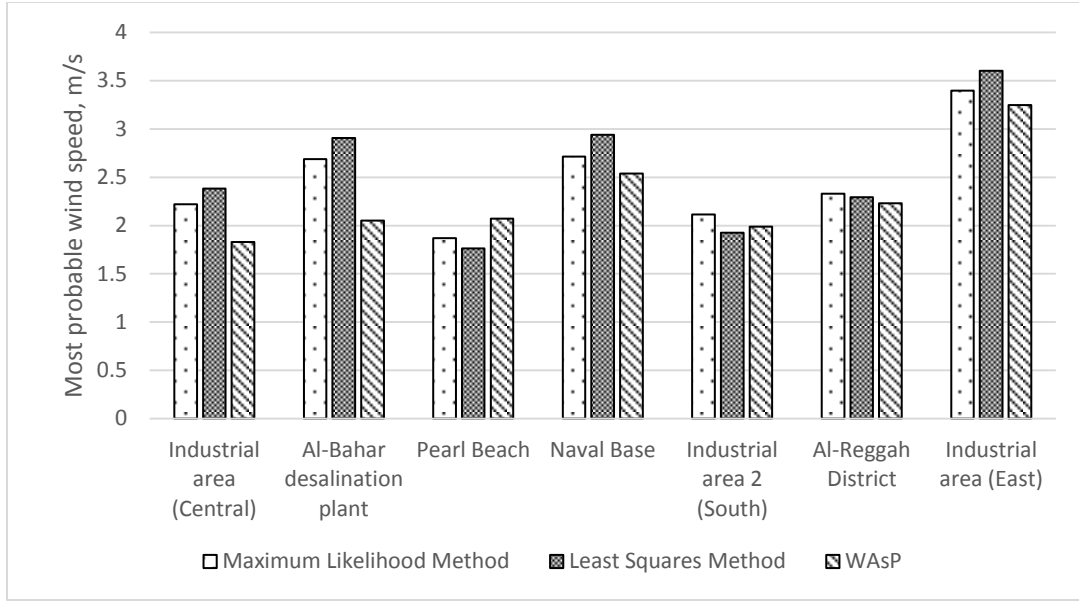


Fig. 13. Most probable wind speed at all sites.

3.4 Maximum Energy Carrying Wind Speed Estimation

The maximum energy carrying wind speed is the speed which generates maximum energy. This can be estimated from the Weibull parameters through the following relationship [19]:

$$V_{max,E} = c \left(1 + \frac{2}{k}\right)^{\frac{1}{k}} \quad (15)$$

The maximum energy carrying wind speed at all the seven locations at 10 m AGL was found using all three estimation methods is shown in Fig. 14 below. The values at each site are in close agreement. The highest maximum energy carrying wind speed values of 8.61, 9.0 and 8.68 m/s; determined by maximum likelihood method, least-square regression methods and WAsP; were observed at Industrial area 2 (south). While at Industrial area (east) the respective values were found to be 7.5, 7.2 and 7.7 m/s respectively. This wind speed is indicative of producing maximum energy in industrial area 2 (south) followed by industrial area (east).

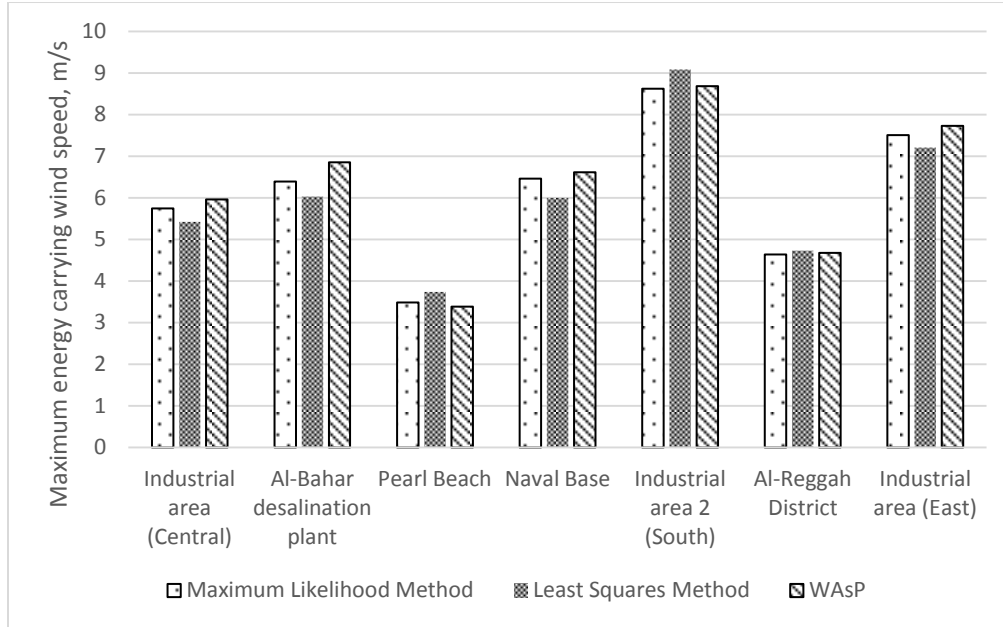


Fig. 14. Maximum energy carrying wind speed at all sites.

3.5 Energy Output

The wind energy output from five different commercially available wind machines with rated power of 1.8 to 3.3 MW was determined at all the sites. The wind speed measurements are typically taken at a height different from the wind turbine hub height. The wind speed can be extrapolated at the hub height by using the wind power law. The wind speed increases with height by a site-dependent power factor known as wind shear coefficient. If the estimated wind shear coefficient is not accurate, the wind power law will lead to an error in the calculation of the wind speed at given hub height and consequently the energy yield estimation [20]. The wind speed frequency at different hub heights was determined by vertical extrapolation of wind speed using the local wind shear exponent value of 0.217. This value of wind shear coefficient was obtained by using measured wind speed at 10, 50 and 90 m heights AGL at Industrial area (central). The air density used in energy output calculations, was calculated using the local pressure and temperature measurements at Industrial area (central). An overall mean air density at this station was found to be 1.17 kg/m³. The technical

specifications of wind machines used in this study are summarised in Table 9. The annual energy output, MWh/year and Plant capacity factor (PCF in %), is presented in Figure 15 and 16 respectively. It can be observed from these figures that the most feasible site for wind farm development in Jubail city is Industrial area (East). At this site, the maximum energy output of 11,135 MWh/year was obtained at a PCF of 41.3% from a commercially available wind machine of 3 MW rated power.

The comparison of % PCF of these five wind machines at all sites reveals that wind machine 5 (1.8 MW rated power) is most efficient at all sites in Jubail. A low rated power wind machine is more efficient for low or mediocre wind potential areas [21]. Wind machines 1, 2 and 4 of rated power 3.3, 3.0 and 2.0 MW respectively were found to have similar mediocre efficiency. Wind machine 3 (2.6 rated power) is found to be least efficient for all sites Jubail.

Table 9 Technical data of wind machines [18]

Wind machine	Cut-in speed (m/s)	Cut-out speed (m/s)	Rated output (kW)	Rated wind speed (m/s)	Hub height (m)	Rotor diameter (m)
WM 1	3	25	3300	12	117	126
WM 2	3	22.5	3000	12	119	126
WM 3	4	23	2600	15	75	100
WM 4	3	25	2000	11.5	80	110
WM 5	4	20	1800	12	80	100

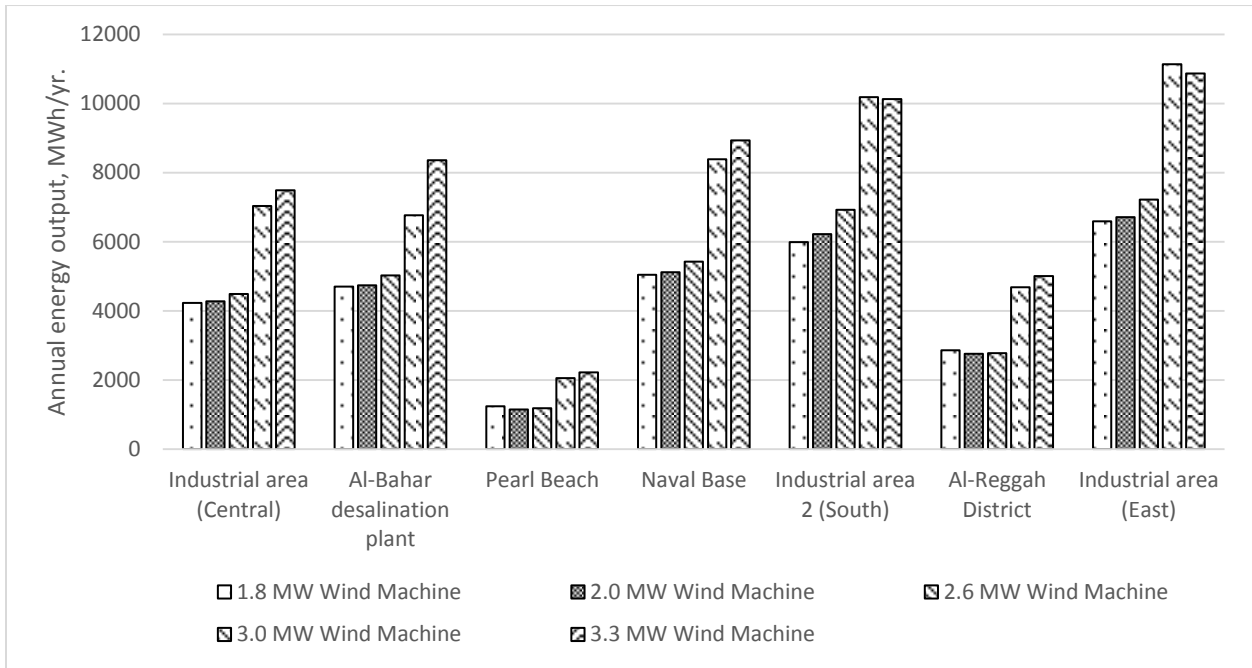


Fig. 15. Annual energy output of different wind machines at all sites.

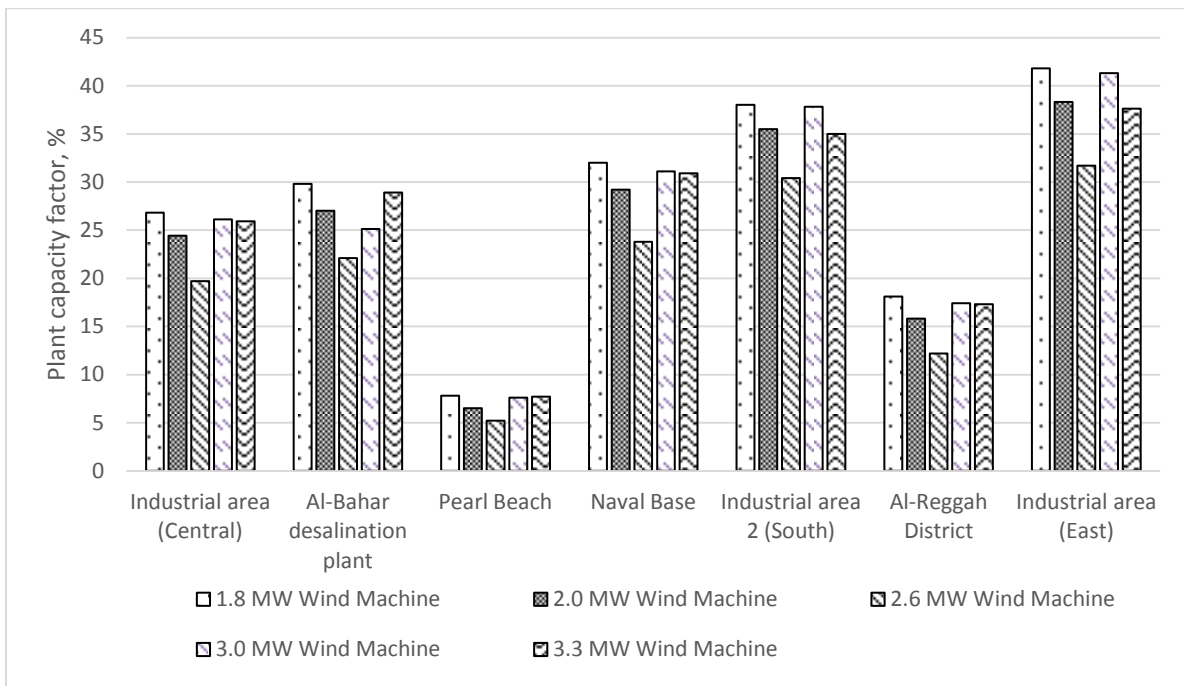


Fig. 16. Plant capacity factor of different wind machines at all sites.

4 Concluding Remarks

The following main observations can be drawn from this study:

At 10 m AGL, the annual mean wind speeds varied from 2.25 m/s at Pearl beach to 4.52 m/s at Industrial area (east) in Jubail industrial area. The highest monthly mean wind speed was observed in February/June and the lowest in September/October. The period of higher winds availability coincides with high power demand period of the area due to air conditioning load. The most prevailing wind direction was from the north-west which means that the wind machines can spread facing the prevailing wind direction.

The maximum likelihood method is found to be the best method of Weibull parameter estimation to represent the wind data in Jubail followed by least square regression method and WASP. The highest value of most probable wind speed was found to be in the range 3.2 m/s to 3.6 m/s at industrial area (east) by three estimation methods. The highest value of maximum energy carrying wind speed was found to be in the range 8.6 m/s to 9.0 m/s at industrial area 2 (south) by three estimation methods.

The wind energy output from five different commercially available wind machines with rated output ranging from 1.8 to 3.3 MW at all the sites shows that most feasible site for wind farm development in Jubail city is Industrial area (East). At this site, the maximum energy output of 11,135 MWh/year with a PCF of 41.3% from a 3 MW rated power wind machine. The second best site for wind farm development is Industrial area 2 (south). At this site, the maximum energy output of 10,180 MWh/year with a PCF of 37.8 % from a 3 MW rated power wind machine. Wind machine 5 (1.8 MW rated power) is most efficient at all sites in Jubail.

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