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Comparative Analysis of Wind Power Energy Potential at Two Coastal Locations in Bangladesh

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ABSTRACT

In this study, wind conditions and its energy potential have been assessed by conducting a Weibull analysis of the wind speed data (over the period of 2002-2011) measured from a port city (Mongla) and an isolated island (Sandwip) in Bangladesh. The monthly mean wind speed at Mongla ranged from 1.60 m/s (December) to 2.47 m/s (April). The monthly values of Weibull shape parameter (k) were from 1.27 to 2.53. In addition, the values of the scale parameter (c) and the monthly wind power density ranged from 1.76 to 2.79 m/s and 3.95 to 17.45 W/m^2, respectively. The seasonal mean wind speed data varied from 1.72 (fall) to 2.29 m/s (spring) with the wind power density from 5.33 (fall) to 14.26 W/m^2 (spring). In the case of Sandwip, the results were comparable to those of Mongla, but moderate reductions in all the comparable variables were observed. The wind data results of these two areas have been compared with those of eight other locations in the world with respect to wind power generation scale. According to this comparison, the wind power generation scale for Mongla and Sandwip was adequate for stand-alone small/micro-scale applications such as local household consumption, solar-wind hybrid irrigation pumps, and battery charging.

Key words: Wind speed, Weibull distribution, Wind energy, Coastal, Energy

1. INTRODUCTION

Wind energy is currently one of the fastest developing renewable energy sources across the globe due to the rapid advancement of wind energy conversion technologies (WECTs). The last decade was characterized by the rapid development of wind power engineering all across the world (Ayres *et al.*, 2007). Since 1996, global wind power capacity has continued to grow at an annual cumulative rate of almost 40% (Asaduzzaman and Billah, 2008). Over the past decades, the installation of wind power generation systems has roughly doubled at every two and a half year cycle. The worldwide wind capacity reached 197,637 MW in 2010 from 93,930 MW in 2007 (Table 1). As of 2010, the wind power capacity of 9,918 MW was newly installed across Europe, with European Union countries accounting for 93.7% of the total (ADB, 2010). Likewise, in many countries, high levels of wind power penetration were achieved to hold the following proportions of stationary electricity production in 2010 (ADB, 2010; Cleveland *et al.*, 2000): Denmark (21%), Portugal (18%), Spain (16%), Ireland (14%), and Germany (9%). As such, wind energy systems have made a significant contribution to the daily life of public in many developing countries. As of 2011, 83 countries around the world are using wind power on a commercial basis. Because of the remarkable growth over the past 20 years, wind power generation is now classified as a mature, reliable, and efficient technology for electricity production (Asaduzzaman and Billah, 2008).

Because of the inherent intermittent nature of wind farm outputs, surveys of estimated wind resources have long been established as a viable tool to determine a particular location for installation and separation of commercial turbines (Khan *et al.*, 2011; Miah *et al.*, 2010; Shell, 2008; Mozumder and Marathe, 2007; Uddin and Ahsan, 2004; Quader, 2002). These surveys are more critical in weather stations where wind energy is fluctuating greatly with low capacity factor (Hossain and Badr, 2007). For a developing country like Bangladesh, the number of advanced monitoring stations (e.g., tower-mounted anemometers) are limited to precisely evaluate the meteorological patterns, direc-

Table 1. List of top 10 countries with wind power generation between 2009 and 2011 (Hossain and Badr, 2007).

Order	Country	Total Capacity (MW)		
		2009	2010	2011
1	United States	35,159	40,298	46,919
2	United Kingdom	4,092	5,248	6,540
3	Spain	19,149	20,623	21,674
4	Portugal	3,357	3,706	4,083
5	Italy	4,850	5,797	6,747
6	India	10,925	13,065	16,084
7	Germany	25,777	27,191	29,060
8	France	4,521	5,970	6,800
9	China	26,010	44,733	62,733
10	Canada	2,550	4,008	5,265
11	Rest of world	21,698	26,998	32,446
12	Total	159,213	197,637	238,351

tional distribution, and vertical wind shear. Because the pre-existing stations provide readings only in the lowest layer of the planetary boundary atmosphere (first 10-25 m in the troposphere), they are not efficient enough to acquire proper data for wind-turbines with conventional power generators (Hasib *et al*., 2011; Wadud *et al*., 2010; WB, 2010; Carta *et al*., 2009; Ramírez and Carta, 2005). This is not pragmatic for the operation of commercial turbines to provide low cost electricity to a large number of households (Rofiqul Islam *et al*., 2008). Information concerning the actual wind profile at varying altitudes hence needs to be accurately estimated, particularly at heights (above 40 m) exploited by medium scale wind-turbines (50 kW-2.5 MW). Such conditions are thus prerequisites to allow an accurate projection of the power output achievable by hybrid wind projects.

In this paper, wind speed data were collected from two coastal locations, Mongla (a port city) and Sandwip (an isolated island) in Bangladesh during the period of 2002-2011 at a height of 10 meter. Then, through an application of Weibull Probability Density Function with its two key parameters (i.e., c scale parameter and k shape parameter) (Fagbenle *et al*., 2011; Mirhosseini *et al*., 2011), the wind energy density and its properties at the two coastal areas were evaluated. To further understand the wind power generation scale of the two target locations, the results were compared with the data sets obtained from eight other locations investigated by other researchers in Iran (Tehran), Nigeria (Enugu, Owerri and Onitsha), Yemen (Al-Mokha), Oman (Seeb and Sur) and Kenya (Mwingi-Kitui). Using the mean wind speed, the relevant parameters (Weibull parameter k and c), wind power density, and wind power generation scale from most of the eight reference areas have been evaluated for comparative purposes (Mukulo *et al*., 2014; Oyedepo *et al*., 2012; Keyhani *et al*., 2010; Sulaiman *et al*., 2002). Based on our analysis, we evaluate the scale of wind energy availability at both Mongla and Sandwip to learn their potential contribution to the local energy budget. The objective is to find out whether these two locations are suitable for small/medium/large scale wind power generation or not.

2. MATERIALS AND METHODS

2. 1 Study Areas

2. 1. 1 Mongla

Located by the Poshur River, Mongla is the second port-city of Bangladesh (Fig. 2). The port has trade links with nearly all major ports of the world (Miah *et al*., 2010). The port is surrounded by the Sundarban mangrove forest. It is located 48 km south of the divisional city Khulna and lies about 100 km north from the Bay of Bengal. Mongla upazila with an area of 1461 km² is located at 22°29′26″N, 89°35′29″E and is bordered by Rampal upazila (north), the Bay of Bengal (south), Morreljang and Sarankhola upazilas (east), and Dacope upazila (west).

The annual temperature portfolio of Monga is plotted in Fig. 2. The climate is generally hot and humid. The average rainfall per year is 428.5 mm (BMD, 2013). The major livelihood of Mongla upazila is linked with the portal activity. Apart from port-linked people (26.7 %), major occupations of the residents include agriculture and related laborer (33.5%), wage laborer (13.4%), service (7.9%), transport (16.3%), fishing (6.2%), and others (1.9%). The urban population of 137,947 can also be divided into 54.7% male and 45.3% female, with a literacy rate of 42.8%.

The Rural Electrification Board (REB), a government owned company is responsible for power transmission and distribution through 33/11/415 kV sub-station and 415 V distribution line (2274 km) in Mongla (PDB, 2007). The sub-station, which covers nine upazilas including Mongolia, has a peak electricity demand of 22 MW per month with the average demand of 17 MW. REB purchases power from the Power Grid Company of Bangladesh (PGCB), which is also a government company responsible for high voltage power transmission throughout Bangladesh.

2. 1. 2 Sandwip

The remote island Sandwip (22.4833°N, 91.4417°E) with a total land area of 762 km^2 is situated at the estuary of the Meghna River on the Bay of Bengal and is separated from the divisional city Chittagong coast by the Sandwip channel (Fig. 1). It has a population of

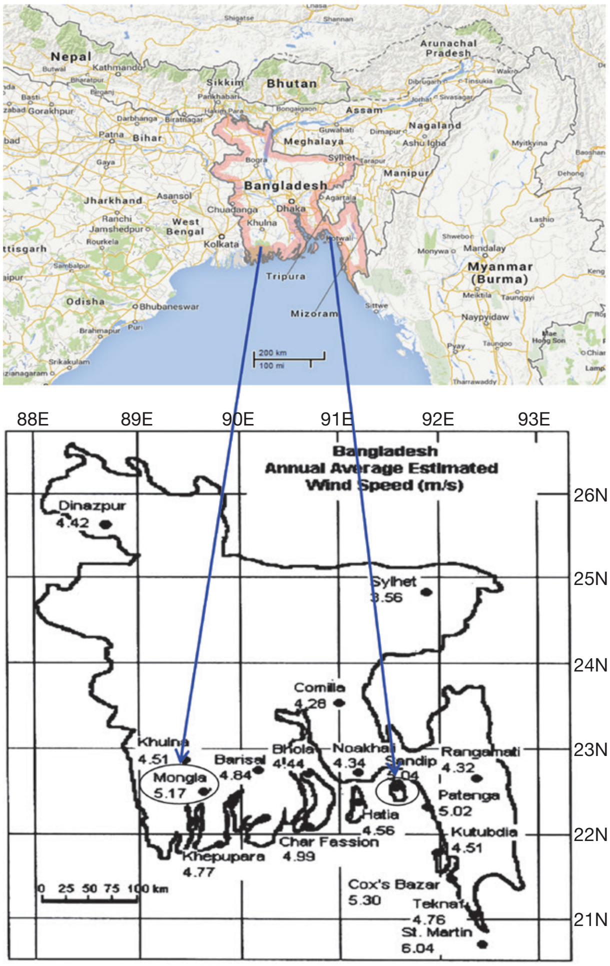

Fig. 1. Average wind speed at Mongla and Sandip along with some potential areas.

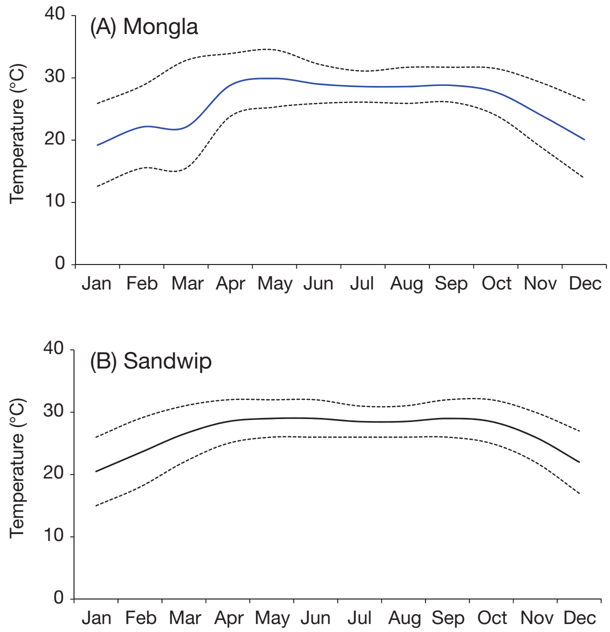

Fig. 2. Monthly mean temperature p of two coastal locations for the whole study period. The solid lines represent the mean value and the dashed lines represent the maximum and minimum.

nearly 272,179 (Males (49.7%) and females (50.3%)). The entire island is 50 km long and 5-15 km wide. The inhabitants' occupations consist of agriculture and related laborer (40.2%), wage laborer (5.5%), service (20.3%), transport (2.1%), fishing (2.7%), business (10.4%) and others (16.4%).

The annual temperature portfolio for Sandwip is presented in Fig. 2. As there is no power supply from the national grid here, the people have to depend on solar panels and diesel generators to match local electricity demand. Several non-governmental organizations (NGOs) have been working to establish and maintain biogas plants on this island (PDB, 2007).

2. 2 Assessment Methods of Wind Characteristics

In order to calculate the mean power delivered by a wind turbine from its power curve, it is necessary to know the probability density distribution of the wind speed (Johnson, 1985). In this study, the wind speed data at the two target locations (Mongla and Sandwip) have been collected at a height of 10 m by the Bangladesh Export Processing Zones Authority (*BEPZA*), which is the official agency of the government to promote, attract and facilitate foreign investment in the Export Processing Zones. The data acquired continuously four times a day (at 6 hour intervals) over a period of ten years (2002-2011) were used for various statistical analyses. The monthly variations of the wind speed measured from each location are plotted in Fig. 3.

2. 2. 1 Probability Density Functions

The probability distribution functions (PDFs) of wind speed can be computed by the assessment of the wind energy potential because it can effectively estimate the performance of wind energy systems for a given location and time (Mirhosseini *et al*., 2011). Although several PDFs have been proposed in the literature, the Weibull PDF, characterized by the two key parameters (c scale and k shape), is one of the preferred choices in analyzing and interpreting the distribution of wind speed to estimate its energy potential (Ramírez and Carta, 2005). The general form of the Weibull PDF can be expressed as follows:

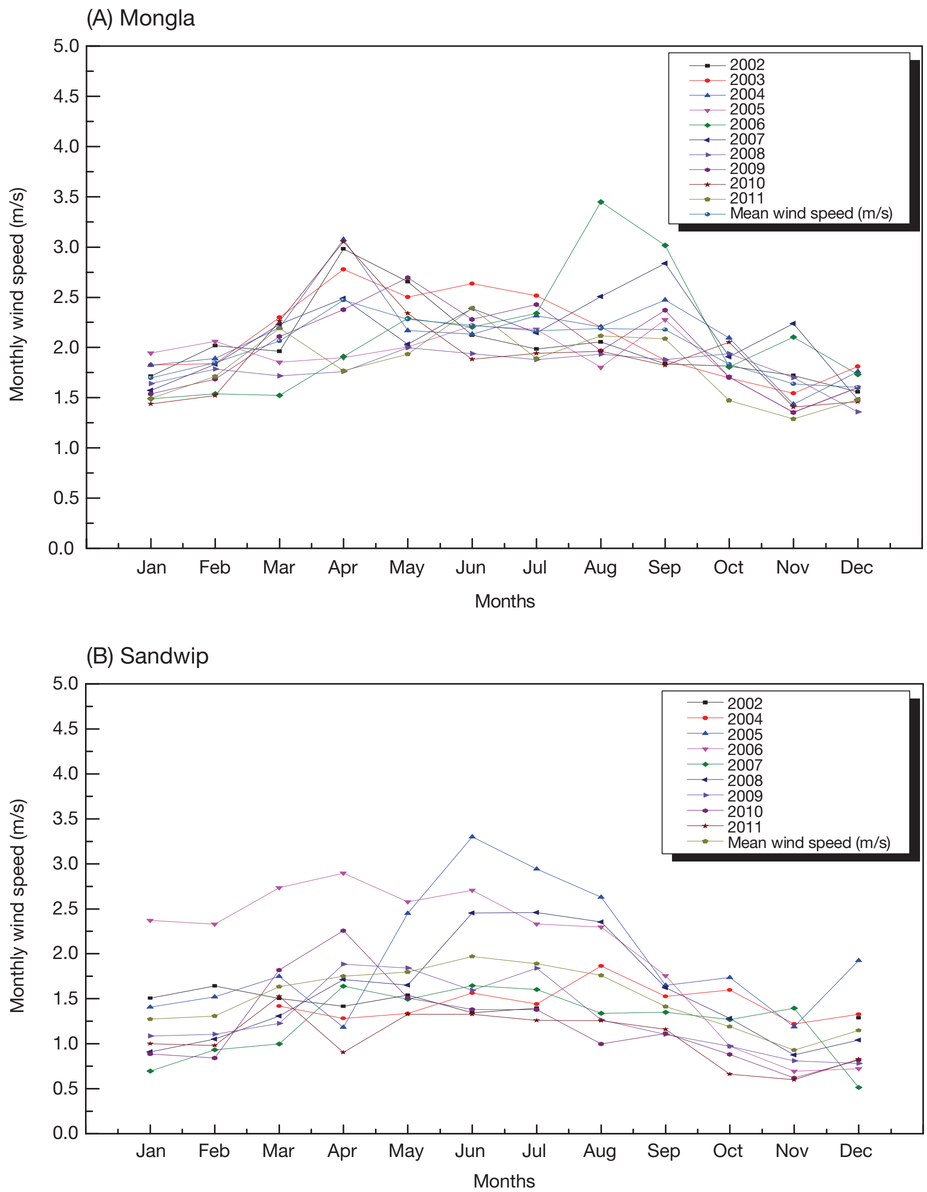

Fig. 3. Plot of monthly mean values of wind speed at two coastal locations for each year (2002 to 2011).

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

where each component of the function consists of the probability of observing wind speed v, k is the dimensionless Weibull shape parameter, and c is the Weibull scale parameter (in unit of speed) [2]. The higher the values of k, the sharper the peak curves become.

The corresponding cumulative probability function of the Weibull distribution can be expressed by the following equation (Ramírez and Carta, 2005):

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

where $F(v)$ is the cumulative distribution function of observed wind speed v.

The two parameters of Weibull PDF, k and c, are associated with the mean of wind speed (v_m) and its standard deviation (σ) as:

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

$$c=\frac{v_m}{\Gamma\left(1+\frac{1}{k}\right)} \quad (4)$$

The mean value of the wind speed (v_m) and its standard deviation (σ) can also be expressed using k and c of the Weibull distribution parameters (MEE, 2010):

$$v_m = c\Gamma\left(1+\frac{1}{k}\right) \tag{5}$$

$$\sigma = c\left[\Gamma\left(1+\frac{2}{k}\right)-\Gamma^2\left(1+\frac{1}{k}\right)\right]^5 \tag{6}$$

where Γ is the gamma function (standard formula). Using the Stirling approximation, the gamma function of (x) can be derived as follows:

$$\Gamma(x) = \int_0^\infty u^{x-1} e^{-u}\, du \tag{7}$$

2. 2. 2 Wind Power Density Function (PDF)

It is well known that the power of the wind at speed (v) through a blade sweep area (A) increases as the cube of its velocity (Wadud *et al.*, 2010).

$$P(v) = \frac{1}{2}\rho A v^3 \tag{8}$$

where ρ is the mean air density (1.225 kg/m^3 at average atmospheric pressure (at sea level) and at 15°C). The wind power density, expressed in Watt per square meter (W/m^2), takes into account of the frequency distribution of the wind speed, the dependence of wind power on air density, and the cube of the wind speed. Therefore, the wind power density is generally considered a better indicator of the wind energy resource.

In order to evaluate the wind resources available at the location, it is important to consider the wind power density, which shows how much energy is available at the location to produce electricity by a wind turbine. The expected monthly (or annual) wind power density per unit area of the location can be expressed, based on the Weibull PDF, as follows:

$$\frac{P_w}{A} = \frac{1}{2}\rho c^3 \Gamma\left(1+\frac{3}{k}\right) \tag{9}$$

2. 2. 3 Wind Energy Density

The wind energy density for a desired duration, T, can be calculated as:

$$\frac{E}{A} = \left(\frac{P_w}{A}\right)T = \frac{1}{2}\rho c^3 \Gamma\left(1+\frac{3}{k}\right)T \tag{10}$$

This equation can be used to calculate the wind energy available for any defined duration with the wind speed frequency distributions data.

3. RESULTS AND DISCUSSION

For the purposes of our study, wind speed data collected from Mongla and Sandwip for the entire study period were used to compute the Weibull distribution parameters (in terms of k and c) and wind power. The salient features of the statistical calculation can be summarized as below.

3. 1 Average Wind Speed at Two Target Sites

The calculation of monthly data for wind speed, Weibull parameters (k and c), and wind power density has been made using equations 3 to 9. The results of this computation are summarized in Table 2. In Mongla, the mean value of wind speed (Fig. 5) varied between 1.60 (Dec) and 2.47 m/s (Apr). On the other hand, in the case of Sandwip, its values were in the range of 0.93 (Nov) to 1.97 m/s (Jun) (Table 2). If the comparison is made by the seasonal intervals, its values at Mongla varied from 1.72 (fall) to 2.29 m/s (spring) (Table 2). In the case of Sandwip, the values changed from 1.22 (winter) to 1.88 m/s in (summer). As such, the relative dominance of Mongla over Sandwip was seen consistently for wind speed data in both monthly and seasonal intervals.

3. 2 Probability Density and Cumulative Distributions

The results shown in Table 2 indicate that the parameters exhibit distinctive patterns across each month. In Mongla, the monthly values of c ranged from 1.76 (Nov) to 2.79 m/s (Apr), while those of k ranged from 1.27 (Nov) to 2.53 (Dec). In terms of the Weibull shape parameter k, wind speed at Mongla was the most uniform in December, while it was the least uniform in November. The monthly probability density data derived from Mongla (Fig. 4) indicate that all the curves tend to share a similar tendency. Likewise, the results from Sandwip (shown in Table 3) indicate that value of c varied from 0.79 m/s (November) to 2.18 m/s (June). Its k values ranged from 0.77 (Nov.) to 1.75 (July). As such, the wind speed data at Sandwip were most uniform in July, while being the least in November.

The probability density and cumulative distribution data obtained by Weibull PDF were also compared between Mongla and Sandwip. In Mongla, the highest mean wind speed (2.29 m/s) was determined in the spring, while the lowest value was seen in the fall (1.72 m/s). The Weibull shape parameter k varied between 1.60 and 2.27, while the scale parameter c varied between 1.95 to 2.59 m/s. The maximum and minimum values of c value were found in spring and fall, respectively.

In the case of Sandwip, the seasonal mean wind speed value varied from 1.22 in the winter and 1.88 m/s in summer. The minimum value of c (1.26 m/s) was also seen in winter, whereas the maximum (2.09 m/s)

Table 2. Summary of wind speed (m/s) and the associated Weibull parameters at the two target sites.

(A) Monthly data

Months	V_m (m/s)	σ	c (m/s)	k	P (W/m^2)	Months	V_m (m/s)	σ	c (m/s)	k	P (W/m^2)
(i) Mongla											
Jan	1.7	0.78	1.91	2.33	4.97	Feb	1.85	0.91	2.09	2.15	6.88
Mar	2.06	1.12	2.33	1.94	10.59	Apr	2.47	1.29	2.79	2.02	17.45
May	2.28	1.2	2.57	2	13.84	Jun	2.22	1.17	2.51	2.01	12.77
Jul	2.17	1.16	2.44	1.98	12.03	Aug	2.19	1.28	2.46	1.8	13.75
Sep	2.18	1.34	2.44	1.69	14.58	Oct	1.83	1.05	2.06	1.83	7.89
Nov	1.64	1.31	1.76	1.27	9.63	Dec	1.6	0.68	1.81	2.53	3.95
(ii) Sandwip											
Jan	1.27	0.89	1.41	1.48	3.49	Feb	1.31	1.04	1.41	1.29	4.79
Mar	1.63	1.13	1.81	1.49	7.35	Apr	1.75	1.21	1.94	1.49	9.03
May	1.8	1.34	1.96	1.37	11.1	Jun	1.97	1.34	2.18	1.52	12.52
Jul	1.89	1.13	2.12	1.75	9.16	Aug	1.76	1.19	1.95	1.53	8.78
Sep	1.41	1.07	1.54	1.35	5.58	Oct	1.19	1.11	1.23	1.08	5.19
Nov	0.93	1.19	0.79	0.77	6.48	Dec	1.15	0.76	1.28	1.55	2.39

(B) Seasonal data

Seasons	V_m (m/s)	σ	c (m/s)	k	P (W/m^2)	E/A (kWh/m^2/season)
(i) Mongla						
Winter	1.97	1.28	2.2	1.6	11.66	25.18
Spring	2.29	1.22	2.59	1.98	14.26	31.5
Summer	2.19	1.2	2.47	1.93	12.81	28.29
Fall	1.72	0.81	1.95	2.27	5.33	11.64
(ii) Sandwip						
Winter	1.22	1.13	1.26	1.09	5.49	11.87
Spring	1.73	1.24	1.91	1.44	9.22	20.36
Summer	1.88	1.22	2.09	1.59	10.14	22.4
Fall	1.25	0.91	1.37	1.41	5.57	7.81

in summer. The values of k are also highly consistent to vary from 1.09 (winter) to 1.59 (summer). Hence, the wind speed appeared to be the most uniform at summer, the least uniform in winter.

3. 3 Wind Power Density

The monthly power densities at Mongla and Sandwip calculated from the Weibull distributions are shown in Fig. 5. The monthly variation of the mean power density for these locations indicates moderately strong variability in the wind power density. It is clear that the maximum and minimum values of wind power density at Mongla are seen as 17.45 W/m^2 (Apr) and 3.95 W/m^2 (Dec), respectively. The obtained results are reported in detail in Table 2. In the case of Sandwip, the maximum and minimum wind power density is computed 12.52 W/m^2 (Jun) and 2.39 W/m^2 (Dec), respectively.

The seasonal variation of the mean wind power density shows that the values in Mongla varied from 5.33 (fall) to 14.3 W/m^2 (spring). Accordingly, the wind power energy was in the range of 11.64 (fall) to 31.50 kWh/m^2/season (spring). On the other hand, the mean wind power density at Sandwip varied from 5.47 (in fall) to 10.14 W/m^2 (in summer). In the case of wind power energy, the values varied from 7.81 kWh/m^2/season (fall) to 22.40 kWh/m^2/season (summer).

3. 4 Comparison with Previous Studies

In order to predict the wind power generation scale at the target sites, the results of a few case studies were examined. The mean monthly wind speed and wind power density are plotted in Fig. 6. The feasibility of wind energy and its potential at these areas were evaluated using the data obtained at 10 m tower height. The average of monthly wind speed values at Mongla (2.02 ± 0.28 m/s) are approximately 25% higher than those of Sandwip with the steady drift throughout the year. The results of these sites are comparable with those measured at Seeb, Oman (2.57 ± 0.32 m/s) (Sulai-

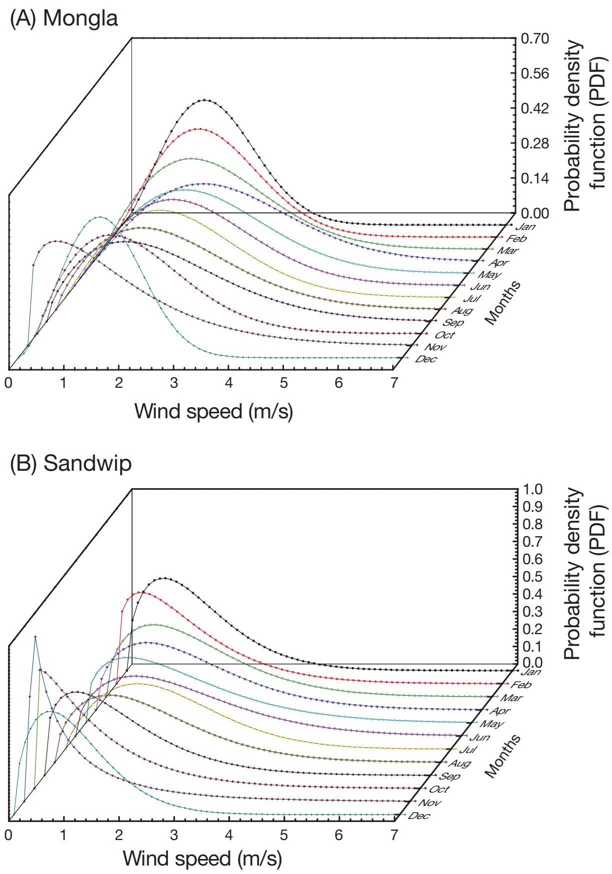

Fig. 4. Monthly wind speed probability density distributions at two coastal locations (2002 to 2011).

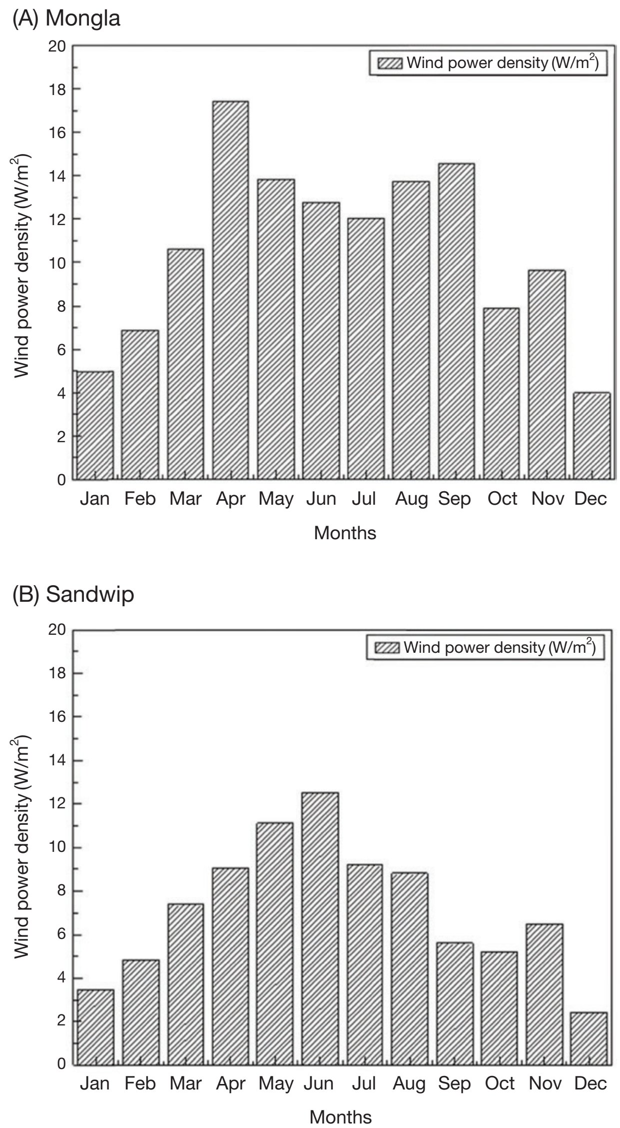

Fig. 5. Monthly wind power density at two coastal locations (2002 to 2011).

man *et al*., 2002). Similarly, wind power density values are quite consistent throughout the year at Mongla, Sandwip, and Seeb, with the average monthly values at 10.7, 7.2, and 19.5 W/m^2, respectively (Fig. 6). In a study made in Oman for wind power generation scale assessment, the Seeb site was marked as a potential site for small or micro scale power generation, whereas the Sur station was found as a potential site for medium scale power generation; the latter showed higher wind speed (55%) and power density (92%) (Sulaiman *et al*., 2002).

Mukulo *et al*. (2014) investigated the wind distribution at Mwingi-Kitui plateau (L8), Kenya which was 50-60% higher than that of Mongla (2.02 m/s); the site was suitable for the small wind turbine generators. At the same site, when the wind power density was measured at 60 m and 100 m height, the calculated values were 84.3 and 115 W/m^2, respectively. This study confirmed the significant increment of wind power density with height (Mukulo *et al*., 2014). In an investigation conducted at Al-Mokha site in Yemen (L5), the site was found to be feasible for medium scale wind power generation and was proposed for a 60 MW wind farm; its wind speed varied from 3.5 (June) to 7.94 m/s (Nov) throughout the year with an overall monthly mean value of 223 W/m^2 of wind power density (MEE, 2010). If we compare the results of our study sites (Mongla) with those of the Al-Mokha site, our monthly mean wind speed and the wind power density are about 3 and 21 times lower than their outcomes, respectively (Fig. 6).

Fig. 6 (A and B) confirms that the prospect of Mongla and Sandwip site is much weaker than all eight reference sites in terms of both mean wind speed and wind power. Overall, the comparison suggests that both sites may be suitable for micro-scale wind power

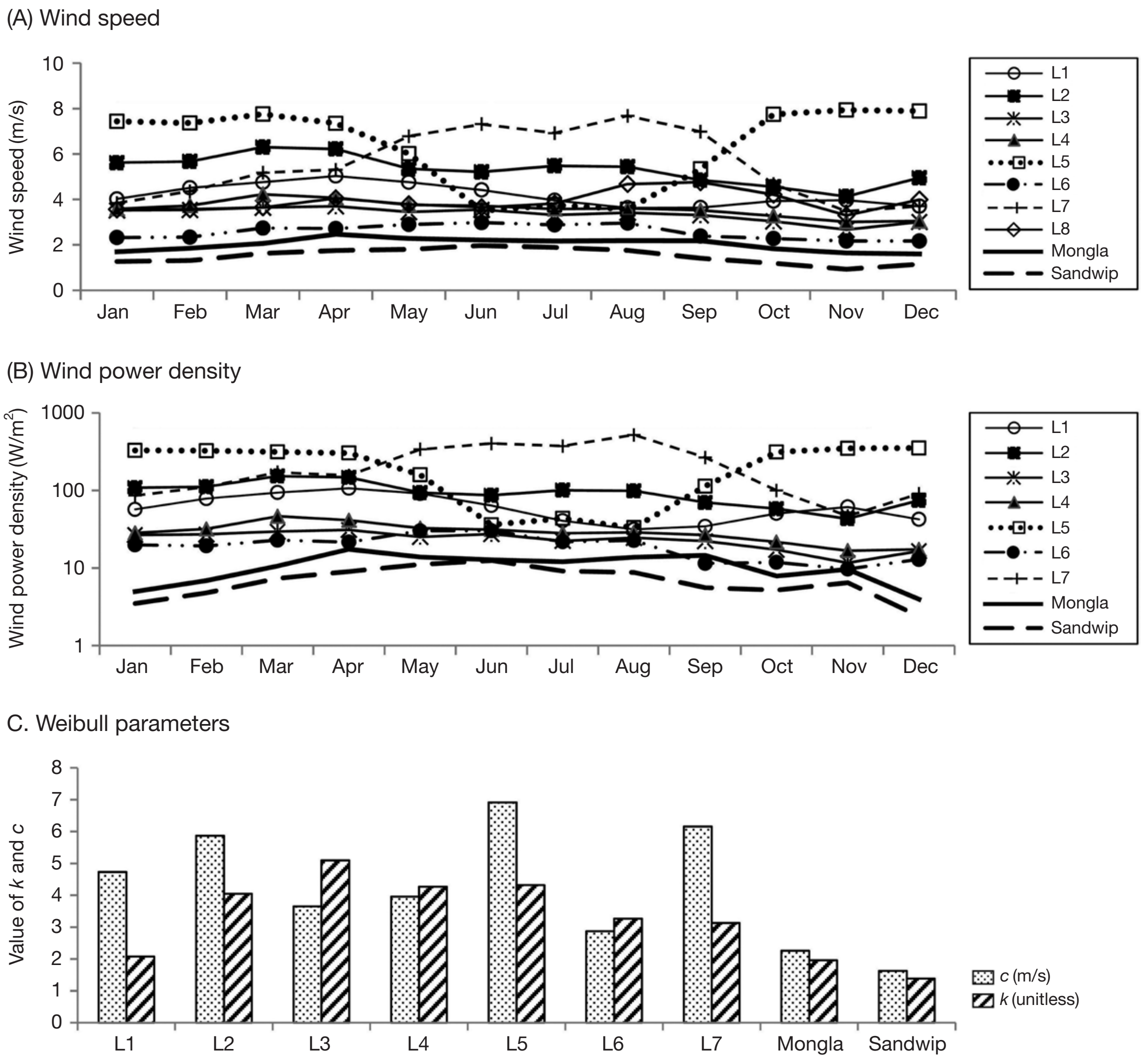

Fig. 6. Comparison between our measurements and previous measurements: A) wind speed, B) wind power density, and C) Weibull parameters. The location codes in the graphs are as follows: (L1): Tehran, Iran (Keyhani *et al*., 2010); (L2): Enugu, Nigeria (Oyedepo *et al*., 2012); (L3): Owerri, Nigeria (Oyedepo *et al*., 2012); (L4): Onitsha, Nigeria (Oyedepo *et al*., 2012); (L5): Al Mokha, Yemen (MEE, 2010); (L6): Seeb, Oman (Sulaiman *et al*., 2002); (L7): Sur, Oman (Sulaiman *et al*., 2002); and (L8): Mwingi-Kitui, Kenya (Mukulo *et al*., 2014).

generation for household needs only. This prediction spans more firmly with the lowest values of Weibul shape parameter (k) and scale parameter (c) at Mongla and Sandwip. Moreover, wind turbines can be used to enhance the project of solar-wind hybrid irrigation pumps to solve the fuel problem at irrigation seasons.

4. CONCLUSIONS

Based on the Weibull Probability Density Function with its two characteristic parameters (c and k), we investigated the general characteristics of the wind speed and wind energy density in Mongla and Sandwip, two coastal sites in Bangladesh. The analysis of wind speed data, collected for the period between 2002 and 2011, can be summarized as follows:

1. The monthly value of Weibull parameters k and c for Mongla varied between 1.27 to 2.53 and 1.76 to 2.79 m/s, respectively. In the case of Sandwip, the monthly value of k and c varied between 0.77 to 1.75 and 0.79 m/s to 2.18 m/s, respectively.
2. In Mongla, the highest and the lowest monthly mean power density values are seen as 17.45 W/m^2 (April) and in 3.95 W/m^2 (December), respectively. In Sandwip, the maximum and minimum

values of monthly wind power density are 12.52 W/m^2 (June) and 2.39 W/m^2 (December).

3. According to this study, both Mongla and Swindip regions exhibited moderately low wind potentials, which should be suitable for operating small wind turbine generators (SWTG). This is a vital information to develop wind energy in two target areas, broadly in the coastal areas of Chittagong and Khulna division.
4. The numerical outcome and probability density distribution curves of the wind speed at two study sites should be very much useful for the Rural Electrification Board (REB), Bangladesh to transmute their solar powered irrigation pump project into solar-wind hybrid powered irrigation project in the investigated regions.
5. Based on the method elaborated in this paper, an assessment of wind energy can be carried out similarly in isolated islands of Bangladesh (such as Kutubdia and Saint Martin), which are strategically very important from a defense point of view, while the national grid is unlikely to expand in near future.

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