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Directional and Time-series Distribution of Projected Wind Profiles based on Low Altitude Data

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Abstract- This paper presents a direction-dependent time-series analysis of forecasted wind profiles for the South Asian country of Bangladesh on the basis of a survey conducted by the United Nations. Representative weather stations are selected from regions of the country with a higher wind potential and directional wind-roses with Weibull density functions are established for the locations at a commercial turbine height. As measured data are available only at lower altitudes (∼10 m), time-series distribution of directional profiles is projected for ≥40 m to assess the suitability of specific time intervals in an annum for wind power extraction. To improve the accuracy of the estimation process, the effects of wind shear coefficient (power profile rule) and log profile parameters are considered on the vertical projection of horizontal wind streams (reaching up to 12.5 m/s for 40-120 m axle heights and 15-80 m rotor diameters). This study is intended to assist the evaluation of the prospects of grid-connected or stand-alone wind-turbines, supporting the renewable power sector of the country.

Keywords- Directional Distribution, Time-series Analysis, Wind Profile Projection.

1. Introduction

The development program of the United Nations has identified investing in the renewable energy sector as a pragmatic way to improve the energy situation of remote localities in the emerging nations of the world [1]. Bangladesh, a developing country located in South Asia, has achieved significant progress in implementing renewable power systems to support its rural electrification projects [2]. Although portable and stand-alone solar panels have been the primary recipients of government funding with regard to 'green' power, wind energy is promising to change this scenario in certain sections of the country which have access to strong wind forces [3]. A program run by the United Nations aimed at evaluating solar and wind resources has identified a number of geographic zones in Bangladesh with sufficient potential of harnessing wind power. When efficiently implemented, a wind energy initiative for a remote region has twofold benefits: it exploits a renewable resource as opposed to petrol or diesel (fossil fuels), and if the region can depend on a stable local resource rather than a foreign supply, the per-unit energy production cost is bound to come down [4]. Existing conventional energy production systems in Bangladesh depend on the burning of coal or natural gas, which inevitably leads to the release of a large amount of harmful fumes and toxic metals to the ambient atmosphere. According to a study published in [5], replacing a small (0.1 kW) generator-driven load with a sustainable supply of energy can save up to 500 kg of carbon-dioxide from being ejected to the atmosphere during a single year. An extensive report published in [6] has found that, if wind power is able to provide for only 10% of a country's energy demand, it would be able to eliminate about one-sixth of the emissions from fossil fuel driven power plants.

To investigate the prospects of installing stand-alone wind turbines in a remote location, a number of atmospheric studies have to be performed before assessing the locally achievable turbine output [7, 8]. A chief limiting factor faced by these initiatives has always been the relative intermittency of wind resources as compared to other forms of renewable energy [9]. Therefore, a time-series analysis of expected profiles at a wind farm location can provide valuable insight on projected turbine output and its dependency on the season of the year [10]. Moreover, concerns related to turbine positioning, propeller architecture and structural engineering need to be addressed with a direction dependent wind resource analysis technique [11]. For a developing nation with limited infrastructural facilities (which usually consist of low-altitude monitoring stations), wind profiles at higher elevations occupied by commercial turbines have to be estimated. The accuracy of this predictions process will depend on a number of geographic and stability parameters. To address these concerns, this paper presents a direction-dependent time-series analysis of projected wind profiles (at ≥40 m) for potential locations in Bangladesh. Suitability of annual intervals for wind power extraction is assessed for sample weather stations while power-profile rule and log-profile law are employed to determine the vertical distribution of horizontal wind speeds (covering 3-12.5 m/s in the 40-120 m height range). The study should facilitate the evaluation of the prospects of planned wind-turbines in remote locations of Bangladesh.

The paper is structured as follows. In section 2, sample local stations are selected for the study on the basis of a UN survey. Section 3 discusses the directional distribution of projected wind profiles. In section 4, a time-series forecasting technique of directional profiles is established. Finally, vertical distribution of horizontal wind streams is predicted in section 5 including the effect of wind shear coefficient and log profile parameters.

2. Data Collection

Typically, the available wind resources in a country are not evenly distributed and may depend on a number of seasonal, atmospheric, topographic and geographic factors. Therefore, any effective estimation of wind profiles has to focus on regions with a higher level of average wind power density. A project run by the wind and solar power assessment program (SWERA) of the United Nations [12] has identified three separate zones on the mainland of Bangladesh with relatively higher potential of extracting wind power. In this paper, they are identified as zone-1 (a long stretch of coastal belt on the country's south), zone-2 (an inland region on the southern and south-eastern borders) and zone-3 (a land-locked section on the northern border). Data are collected through anemometer towers (average height 12 m) located on weather stations based in these regions and maintained by the national meteorological department [13]. To establish a long observation interval, time-series recordings for a ten year period (1998-2007) are analyzed with directional analysis being performed for the year 2007. Eight sample weather monitoring posts are considered for the three zones, which are geographically located at Cox's bazaar (21.4n 91.9e, zone-1), Hatiya (22.4n 91.1e, zone-1), Bhola (22.7n 90.5e, zone-1), Barisal (22.8n 90.3e, zone-2), Patuakhali (22.3n 90.3e, zone-2), Khepupara (21.98n 90.2e, zone-2), Saidpur (25.8n 88.9e, zone-3), and Rangpur (25.7n 89.2e, zone-3).

3. Time-Series Distribution of Directional Profiles

3.1. Wind-rose

The directional distribution of wind resources available at a turbine location needs to be investigated to address the design concerns related to turbine positioning before installing low-to-medium scale wind plants. Wind-rose is a typical meteorological tool which can give an estimate of prominent flow directions and ranges for wind velocity naturally available at a wind monitoring station [11]. Three weather posts are selected from the potentially resourceful zones in Bangladesh, as discussed in section 2, and the corresponding directional wind-roses are plotted in Fig. 1(a), 1(b) and 1(c), respectively. Annual time-series data for the year 2007 are considered in these figures. The relative length of the spokes in theses curves represents the percentage share of a laminar wind stream flowing from a particular direction. For the station with the strongest wind streams (Cox's Bazar, located in zone-1), 58% of available horizontal wind flows from the southern direction. Wind flows are available with a lower share (25 and 17%, respectively) from two other directions (north and north-east). The situation remains somewhat similar for prominent wind directions in zone-2 (Barisal) with smaller shares (about 8%) covering eastern, western and north-western courses. The scenario is changed for zone-3 (Saidpur) with the majority of the streams (58%) now flowing from the east. The nationwide directional wind-rose based on average (50

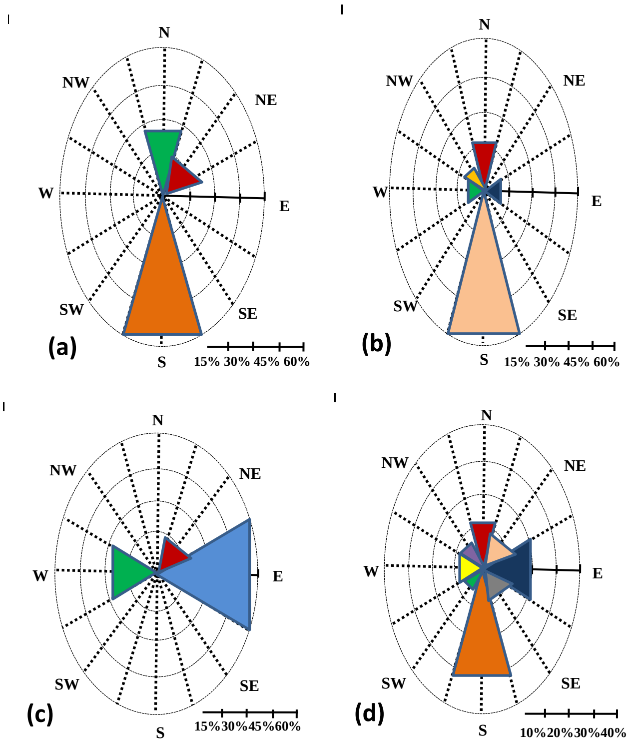

Fig. 1. a) Directional projection of wind velocity at 50m (wind-rose) for zone-1 (Cox's Bazar) b) wind-rose for zone-2 (Barisal) c) wind-rose for zone-3 (Saidpur) d) directional wind-rose for the country based on 50m (average) wind profiles

m) wind profiles for 2007 is shown in Fig. 1(d), which indicates that 31 and 19% of mean directional readings cover the southern and the eastern bearings, respectively. The spokes of the rose plots are not drawn in the same scale, so a measuring standard is included in each figure. The readings suggest that three major wind courses are applicable for the available wind profiles in Bangladesh and they are categorized with the acronyms S/SE/SW, E/NE, and N/NW, respectively.

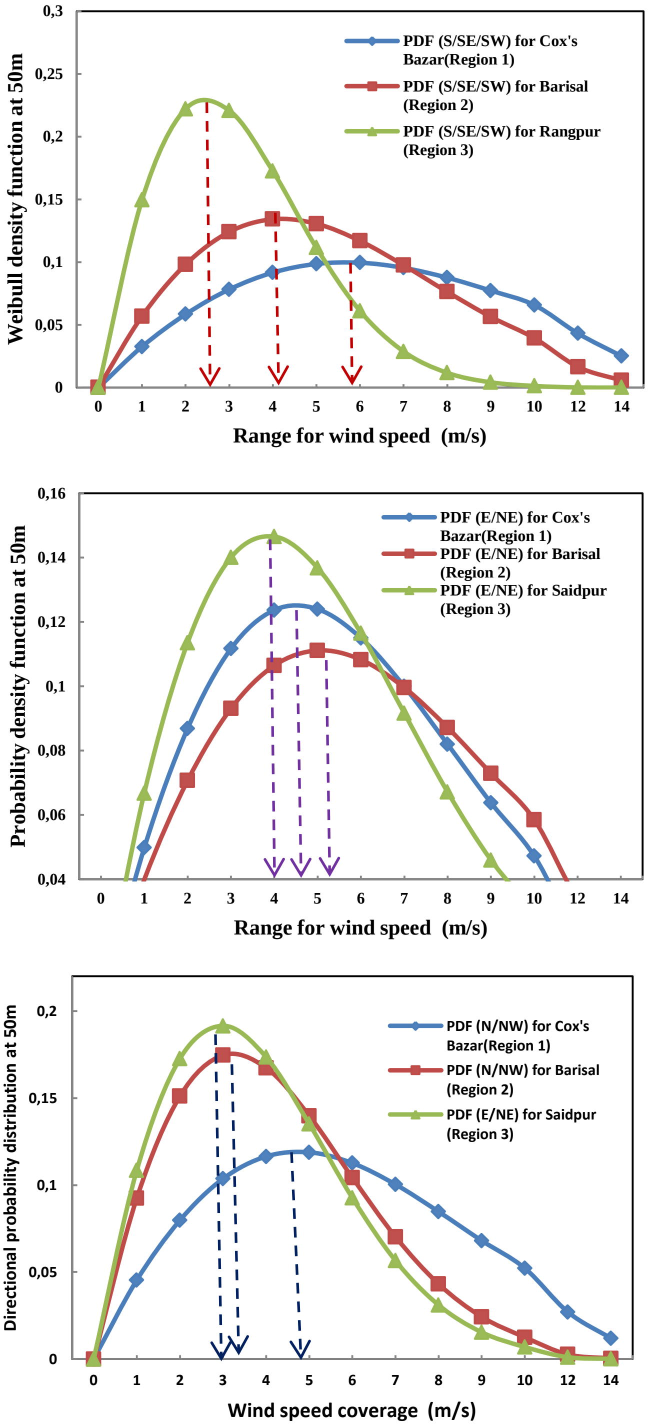

Fig. 2. Weibull density function versus available wind speed for the directions of a) S/SW/SE b) E/NE c) N/NW

3.2. Directional Probability Distribution

After the distribution with regard to wind direction is covered with wind-roses for the selected stations, the next step involves evaluating the Weibull density function [14] for the three specified directions. With this objective, 50 m wind profiles are derived employing the 1/7th power law from base wind data collected at lower altitudes (around 10 m). It provides an estimate of the range of velocities which will be available in the concerned directions. The Weibull function exploits a site-dependent scale parameter (derived from mean wind velocity) and a shape factor (derived from profile shape) to calculate the probability distribution of wind speed coverage for a station [15]. The scale parameter (c) is defined with a simplified first-order gamma function Γ(), as expressed by

$$c = \bar{v}/\Gamma(1+\frac{1}{k}), (c>1) \tag{1}$$

where k is the Weibull shape factor. $\bar{v}$ is the average site velocity at an elevated height for a particular direction, which is defined by

$$\bar{v} = \frac{\sum_{j=1}^{n} f_j v_j}{\sum_{j=1}^{n} f_j}, \tag{2}$$

where f_j is the frequency of occurrence for a speed category (v_j) and n is the number of categories under observation. If we define σ as the standard deviation from mean velocity in a specified direction, then the k factor relates with the average velocity through

$$k = (\frac{\sigma}{\bar{v}})^{-1.086} (k>0), \tag{3}$$

where -1.086 is an empirical constant. Here, k remains confined within a statistical limit and based on the reports of published results [10], [16], its standard value is taken as 1.91. After truncating higher order terms for simplicity, the $\Gamma(1+1/k)$ function takes the form of [17]

$$\Gamma(1+\frac{1}{k}) = 0.825 + 0.0135k + \exp[-(2+3(k-1))]. \tag{4}$$

With these data samples, the probability of a wind stream flowing at a turbine height with a certain velocity (v_j) can be calculated as

$$f(v_j) = \frac{f_j}{\sum_{j=1}^{n} f_j}, \tag{5}$$

But, to improve prediction accuracy, a better choice for estimating the probability of occurrence for a wind speed is achieved by employing the Weibull density function. It is defined for a wind stream with velocity v flowing from a specific course:

$$f_w(v)=\frac{k}{c}\left(\frac{v}{c}\right)^{k-1}\exp\left[-\left(\frac{v}{c}\right)^{k}\right](v>0),\quad =0(v\le 0), \tag{6}$$

Fig. 2(a)-2(c) plot the probability distribution functions (*pdf*) for the three dominant bearings showing significant difference in achieved velocities. The first and second regions in Fig. 2(a) cover a wide range of velocities (1.5-11 m/s at 50 m) with scale factors of 8.4 and 6.2 m/s, respectively. Region-3 covers a narrower window and its scale parameter is read as 3.6 m/s. The three regional density functions for the direction of E/NE in Fig. 2(b) achieve similar peak ranges (4.8, 5.3 and 4 m/s, respectively) with the highest scale factor now achieved for region-2 (Barisal). For the third wind category (N/NW), regions 2 and 3 span across smaller windows (c=4.8, 4.3) in Fig. 2(c). The overall scenario suggests that profiles above 5 m/s at an elevation of 50 m will be achieved for zones 1 and 2, predominantly flowing from southern and eastern courses.

4. Time-Series Distribution of Directional Profiles

4.1. Monthly Distribution of Forecasted Data

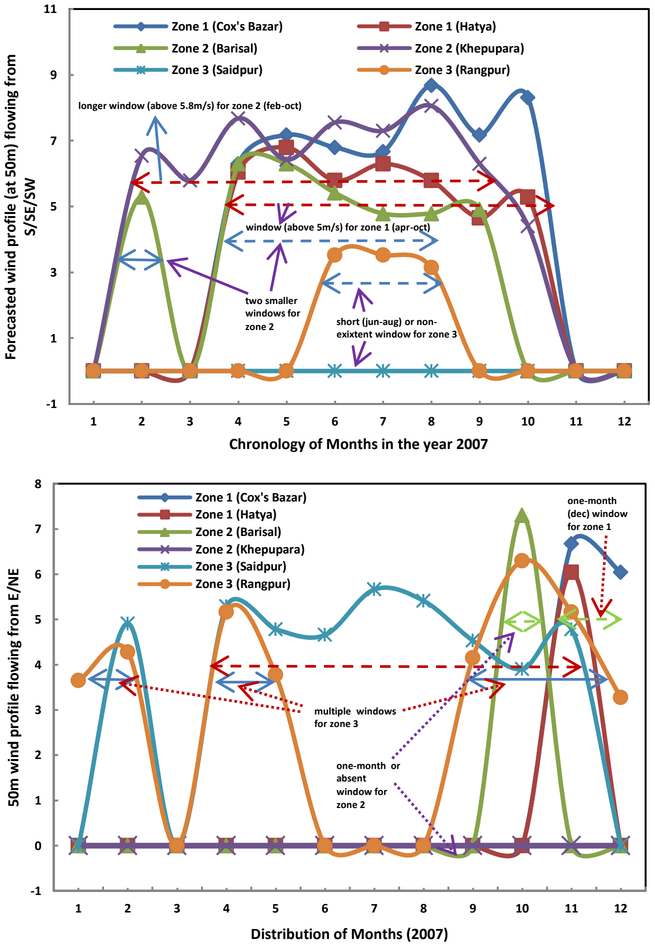

Fig. 3. a) Monthly distribution of forecasted wind profiles (at 50 m) flowing from the south/south-east/south-west b) wind profile distribution for the eastern/north-eastern direction

The intermittency of useful wind resources is considered as a chief limiting factor for making accurate projections of power outputs from grid-connected wind turbines. A time-series distribution analysis performed in a regulated manner can help in this regard by identifying existing windows in an annum when regular streams can be expected at a turbine location. This analysis can be performed in an hourly fashion, but for a long-term forecasting model (duration of one year or more), a monthly statistics will provide a more useful assessment. If wind bearing is included in the time-series analysis, it would add a third dimension to the density functions for a particular weather station (derived in the previous section).

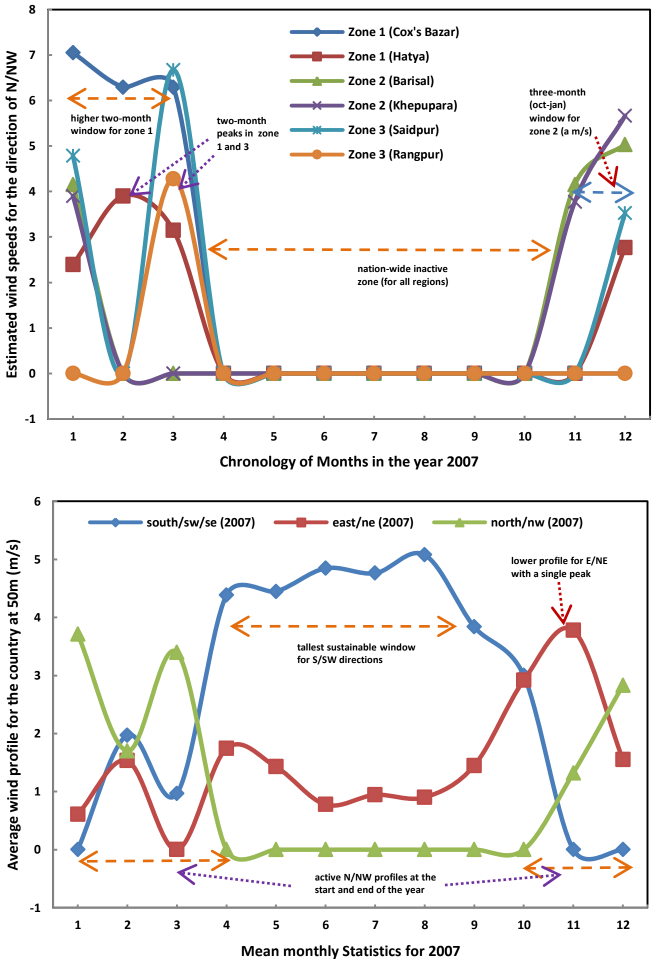

Fig. 4. a) Estimated wind speeds for the northern/north-western direction b) time-series distribution of average wind profiles for the country

The forecasted wind profiles (at 50 m) covering the three major wind routes are the subjects of Fig. 3 and 4. Fig. 3(a), 3(b), and 4(a) are plotted for six selected stations from the three potential windy zones of Bangladesh. Raw data are collected from anemometer readings (with wind route information) at a lower height and profiles are projected to 50 m for assessing the prospects of a medium-scale (<500 kW) turbine. For the southern wind bearing (S/SW/SE), a seven month (April-October) window is available for the stations in zone-1 where wind speeds are consistently greater that 5 m/s. In case of the two locations in zone-3, southern winds do not exist for Saidpur and only a limited three-month window is available for Rangpur. Zone-2 (Khepupara) provides a wide coverage of ten months (February-November), with readings reaching up to 8.5 m/s. Instances of two discrete windows existing at the start and the middle of the year are manifested for a station (Barisal). The time-series data covering the eastern route in Fig. 3(b) present one-month or non-existent active periods for the stations in the first two zones. Sustainable peak speeds reaching 5 m/s or above are achieved only for the two stations in zone-3 (Saidpur and Rangpur). A nation-wide idle window (with no measurable wind activity) exists for the three potential zones during the long period of April to October for northern winds [see Fig. 4(a)]. Short-spanning single-peak coverage is available for this bearing at the start of the year. After analyzing the data from the six stations, monthly distribution of average wind profiles for the entire country is presented in Fig. 4(b). It conforms to the previous readings and indicates that a nationwide sustainable window is available for southern winds during the March-September period. The E/NE profile has a lower base value and a peak during the month of December. The window for the N/NW route covers the Nov-Feb period but changes very sharply, which will prevent any significant extraction of turbine power.

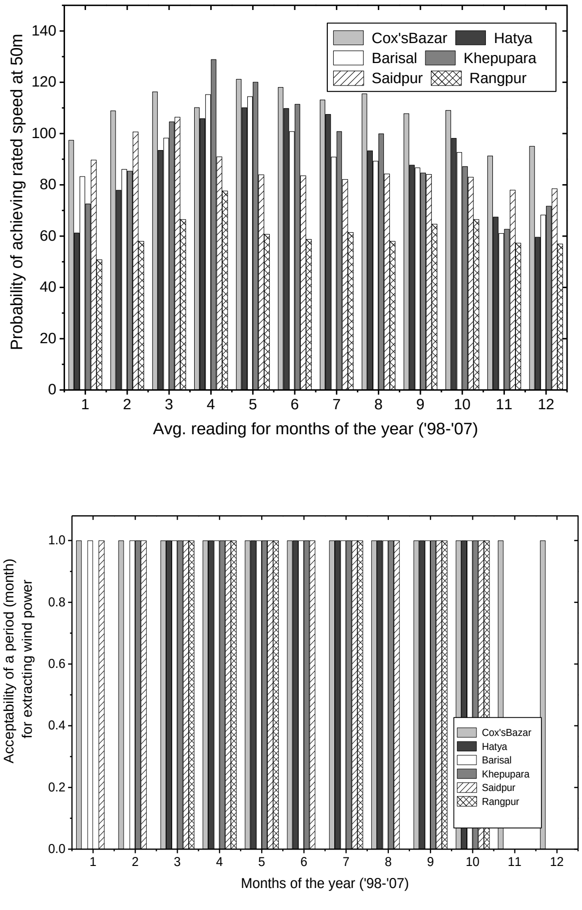

Fig. 5. a) Probability (in percentage) of achieving the rated speed for a 500 kW turbine b) time-series potential assessment for extraction of wind power

4.2. Suitability of Intervals for Wind Power Extraction

To evaluate the acceptability of a period (month) for extracting wind power, Fig. 5(a) presents the time-series probability P(*site*) (in percentage) for the selected stations of achieving the rated speed for a 500 kW turbine, proving Cox's Bazar (zone-1) to be the strongest candidate. The rated speed is deetermined by the effective turbine output and the standard is set as 7 m/s for a 500 kW wind turbine (axle height 50 m, rotor diameter 35 m) [18]. If a stations crosses the 80% mark for a particular month, the period is deemed suitable for efficient wind-turbine operation. When the results are plotted in Fig. 5(b) to make a comparative assessment with the monthly bars indicating the fulfilment of the specified criteria, nine months pass the limit for zone-1 (Cox's Bazar), while for zone-3 (Saidpur) turbine operation is possible for only three months. The condition used for the figure is

$$Acceptability = 1(if P_{site} > 80), \tag{7}$$

and it may be relaxed for a station with lower wind potential. These findings can be exploited during the planning phase for new turbines and in preparing the maintenance schedule for a wind-turbine facility in the selected locations.

5. Vertical Projection of Horizontal Streams

With measured data available only at near-ground altitudes, vertical projection of laminar (horizontal) wind flow gains additional importance as a tool for estimating wind speed. The elevation occupied by typical commercial turbine axles resides in the range of 40-120 m (with a turbine output of 50-2000 kW), which necessitates forecasting of wind velocity in this range in the absence of tower-mounted recording equipments at the location.

5.1. Effect of Wind Shear Coefficient (WSC)

Wind shear coefficient (WSC, denoted by ψ) is a site-dependent empirical parameter, which relates readings of wind velocity measured at different heights within the lower planetary boundary layer (up to 200 m from ground level). It may behave as a constant if the difference in the readings is not too great. The particular value of the parameter depends on the presence of vegetation and physical obstacles at or around tower level and the stability of the atmosphere. It can be estimated using measured wind speed readings ($V_{hi/lo}$) at the relatively low altitudes H_{hi} and H_{lo}:

$$\psi = \frac{\log(V_{hi}/V_{lo})}{\log(H_{hi}/H_{lo})}, \tag{8}$$

The shear coefficient can be estimated more accurately with the following expression if a number of speed recordings (V_i) are available at higher altitudes (H_i) other than the reading at base elevation (V_o for H_o) [11]

$$\psi = \frac{\sum_i [\log(V_i/V_o)\log(H_i/H_o)]}{\sum_i [\log(H_i/H_o)]^2} \tag{9}$$

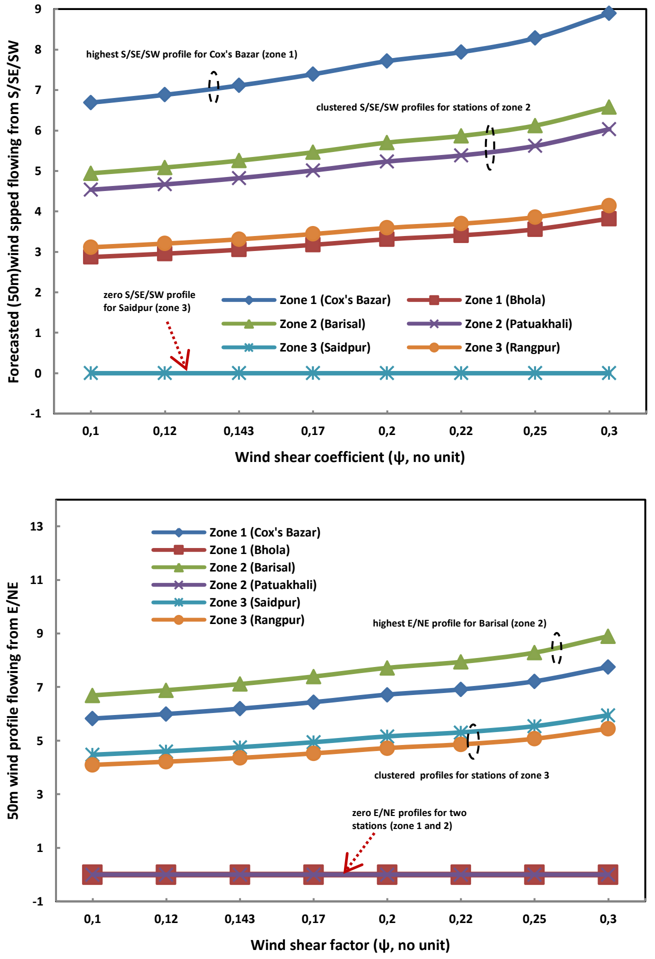

Fig. 6. a) Effect of variable wind shear coefficient on southern forecasted speed profiles b) wind shear controlled distribution of 50 m eastern wind profiles

The 1/7th power law assumes a constant value of 0.143 for the coefficient, ignoring the effect of obstacles and considering neutral stability in the atmosphere. The shear coefficient (ψ) works as the basis of the general wind power law [7], an important rule used for projecting wind profiles (V_{tur}) at heights occupied by a typical turbine (H_{tur} =40-120 m) which is expressed by

$$V_{tur} = (\frac{H_{tur}}{H_{anem}})^{\psi} .* V_{anem}, \tag{10}$$

where V_{anem} is collected from a tower mounted anemometer at the weather station at the height of H_{anem}. Depending on the proximity of a wind-mill to water bodies and topographic anomalies in the surrounding area, the shear coefficient may vary between 0.1 and 0.3 and affect the directional distribution of projected wind curves. As examples, effects of variation in the wind shear coefficient on southern and eastern forecasted profiles (at 50 m) are discussed in Fig. 6(a) and 6(b), respectively, for the three hotspots of Bangladesh. They show a zero profile for Saidpur (zone-3) and strong winds for Cox's Bazar (zone-1, reaching 6.8 to 9 m/s at 50 m) in Fig. 6(a). Zone-1 also has low potential stations (Bhola) and the stations in the second zone have clustered profiles (covering 4.5-6.3 m/s). The eastern profiles manifest significant strength (6-8.8 m/s) for two stations (Barisal and Cox's Bazar) while Patuakhali and Bhola do not record any stream flowing from this direction. All six stations record low-to-medium profiles for north/north-western wind streams in Fig. 7(a). Therefore, when the national average directional distribution is recorded against WSC in Fig. 7(b), it shows a significant difference between the course of E/NE (3.2-4.25 m/s) and the two remaining categories (3.8-5 m/s).

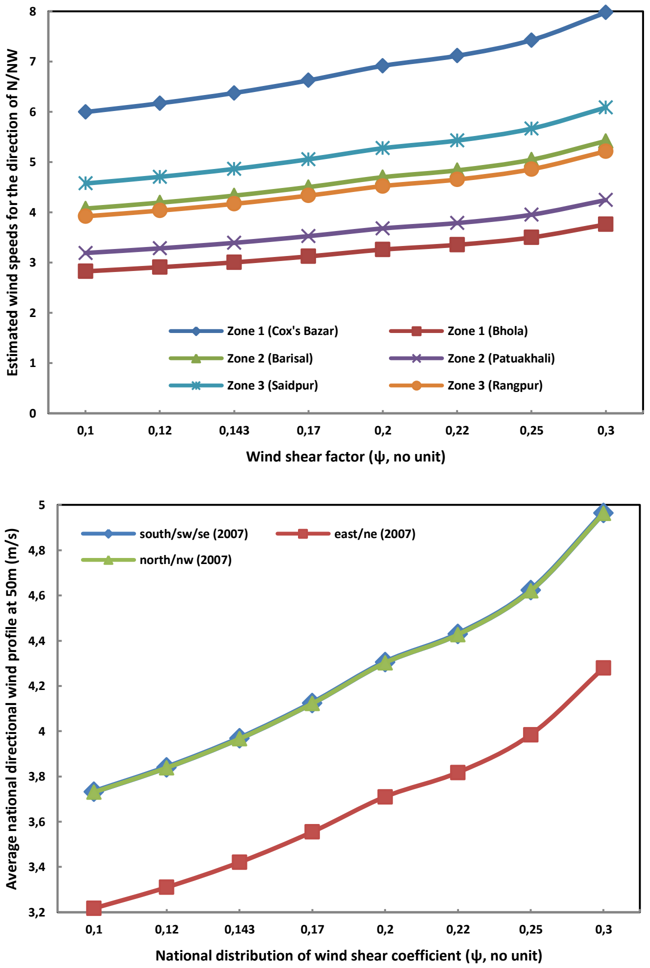

Fig. 7. a) Estimated wind speeds (N/NW) against a variable wind shear factor b) average directional wind profiles for the country (in m/s)

As wind power density (*WPD*) can describe wind resources more accurately than wind velocity, the mean profile reading $V_{tur}(t)$ taken over a specific time period *T* can be employed to derive *WPD* for the location:

$$WPD = \frac{1}{2}\frac{1}{T}\int_0^T \rho V_{tur}(t)^3 dt\ , \tag{11}$$

where ρ denotes the mean density of air for the weather station and can generally be considered as a constant. If the mean reading of projected wind speed is $\overline{V_{tur}}$ and the variance in velocity is calculated as σ^2 [19], then *WPD* can also be estimated with

$$WPD = \frac{1}{2}\rho[\overline{V_{tur}}^{3} + 3\overline{V_{tur}}\sigma^{2}]. \tag{12}$$

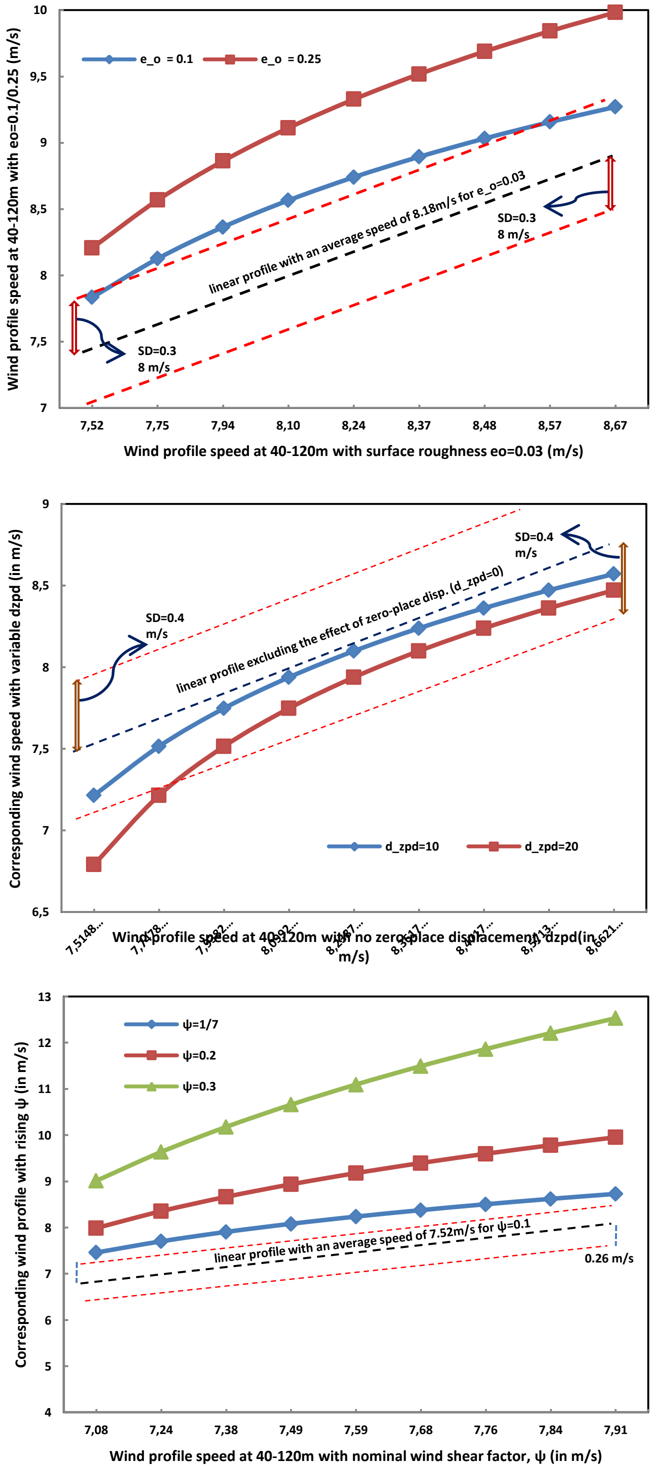

Fig. 8. Effect of a) surface roughness b) zero-place displacement and c) wind shear factor on general wind profile speeds (axle height 40-120 m)

5.2. Influence of Log Profile Parameters

The wind power law (equation 10) has a number of limitations which may affect the accuracy of profile projection in the planetary boundary layer. It assumes neutral stability in the ambient atmosphere and does not consider roughness data during the assessment of wind resources. A semi-empirical log profile, therefore, is often employed for the study of wind resources which addresses the shortcomings of the power law. When a logarithmic law is utilized to anticipate possible wind velocities at a turbine altitude, the effect of a number of controlling parameters should be investigated to ensure maximum forecasting accuracy. Judicial selection of these parameters apposite for a particular monitoring station is also a necessary step. The station of Cox's Bazar in zone-1 is selected as the sample weather post to evaluate this process as it has proved to be a strong candidate for harnessing wind energy.

5.2.1. Surface Roughness

As mentioned in the previous section, wind shear coefficient for a turbine location typically depends on atmospheric conditions and topographic features. In case of a log profile, surface roughness is defined as a corrective measure which takes the abrasiveness of general ground features into account by incorporating an extra discounting factor (e_o) in the estimation process. This factor is called roughness length which may vary between 0.03 and 0.25 for the selected stations (as they are generally devoid of dense forest areas and typically located near croplands). The basic form of the log profile [20] including the effect of e_o measures wind profile (V_{tur}) at a turbine height H_{tur} with

$$V_{fr} = \frac{V_{fr}}{\kappa}\ln(\frac{H_{tur}}{e_o}),\text{`} \tag{13}$$

where *k* is a dimensionless parameter named as Karman's factor [21]

$$\kappa \approx 0.41,\text{`} \tag{14}$$

and V_{fr} defines the friction velocity depending on the movement of wind stream around surface of obstacles. Fluid dynamics defines V_{fr} as a logarithmic function

$$V_{fr} = \frac{\kappa V_{anem}}{\ln(\frac{H_{anem}+e_o}{e_o})}. \tag{15}$$

This section considers a basic profile which is most likely to fit a majority of the wind stations in Bangladesh and measures the deviation of projected wind curves against variable profile controlling factors. For example, in Fig. 8(a), the log rule is used to derive a basic wind profile covering wind speeds achieved in the range of 40-120 m. Roughness length (e_o) for this profile is taken as 0.03, a value applicable for a farm located on flat grasslands. In the next step, projected wind curves are plotted against the basic profile for a variable roughness length (e_o=0.1-0.25). If a change in the value of e_o had no influence on the forecasted profiles then the projections would have been perfectly linear (blue dotted line) with a mean reading of 8.18 m/s. The boundaries set by standard deviation (SD=0.38 m/s) of estimated velocities are represented by the red dotted lines for the concerned range of heights. A roughness measure of 0.1 (appropriate for a combination of flat and croplands) raises the profile while still remaining close to the upper boundary set by the SD. Commonly featuring obstacles (e_o represented by 0.25) may push the profile even higher outside the SD boundary, where the reading at a height of 120 m increases up to 10 m/s. For e_o=0.1, the velocity covers 7.67 to 9.2 m/s. So, profile prediction is sensitive to topographic considerations and roughness length should be set carefully depending on the particular setting of a windy location.

5.2.2. Zero-place Displacement

A second control parameter included in a log profile is called zero-place displacement (d_{zpd}), which represents a virtual height where stream speed drops to zero because of the presence of significant local obstacles. The log profile including a zero-place displacement parameter takes the form of

$$V_{fr} = \frac{V_{fr}}{\kappa} \ln\left(\frac{H_{tur} - d_{zpd}}{e_o}\right),` \qquad (16)$$

Like the previous example, the basic profile for this setting has been obtained excluding the effect of d_{zpd} (appropriate for the selected station in Cox's Bazar). With the average height of vegetation existing in the station areas reaching up to 30m, d_{zpd} could have a value which is two-third of the obstacle coverage. Raising the magnitude of d_{zpd} to this limit (20 m) pushes down the profile but it still remains well within the SD boundaries in Fig. 8(b). So, the influence of d_{zpd} on log profile proves to be less dominant when compared with that of roughness data. Nevertheless, if d_{zpd} is modelled with 20 m in the presence of obstacles surrounding a 40 m turbine axle, corresponding projected wind speed drops down from 7.51 to 6.75 m/s.

5.2.3. Wind Shear and Wind Curves

The procedure outlined in the preceding subsections is also applicable for wind shear coefficient (WSC), which was obtained by equation (10) for the power law. In this case [Fig. 8(c)], the basic profile (obtained for ψ=0.1) shifts by a greater amount for a rise in the shear factor, leading to the conclusion that WSC exerts a stronger influence on wind profile forecasting and proper assessment of wind resources should be performed before assigning a wind shear factor to a weather station.

6. Conclusions

This paper assesses the feasibility of installing small-to-medium scale wind-turbines (50-2000 kW) to boost the struggling rural power sector of Bangladesh through guesstimation of commercial wind profiles. It projects relevant high-altitude (turbine height: 40-120 m, rotor coverage: up to 80 m) wind profiles from data collected by local weather stations at a lower elevation (~12 m). The study is based on a survey conducted by the environment program of the UN to identify potential installation points in the country. By establishing a time-series distribution of direction-dependent wind profiles, it identifies suitable intervals in an annum for wind power extraction and their dependence on dominant stream directions. Density functions are calculated to estimate the achievable range of wind speeds in a particular direction (at 50 m). The behaviour of the profiles against variable shear coefficient is established. Deviation of the estimated wind curves (0.1-1.5 m/s) against log-profile parameters, e.g. surface roughness and zero-plane displacement, is analyzed to highlight the limitations of the wind power law. The study is intended to assist planning of installing grid-connected or stand-alone wind-turbines to improve the power situation in remote localities of Bangladesh.

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