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Derivation of Surface Roughness and Capacity Factor from Wind Shear Characteristics

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Abstract-In this paper, a novel method to derive surface roughness for the location of a wind-turbine facility is explained. Employing measured and projected low altitude (~10-30m) meteorological data, wind shear coefficients are estimated for weather stations in Bangladesh with potential for harnessing wind energy. Diversely located geographical positions are covered from three national sectors on the basis of surveys conducted by the United Nations. Time-series (annual and monthly) variation of wind shear is exploited to produce a forecasting tool for wind profile at commercial turbine heights. Best estimates of average shear factors (in the range of 0.1 to 0.3) are obtained from probability distribution curves and by matching their profiles with forecasted wind curves, roughness length is determined for specific weather points. The findings (varying from 0.05 to 0.5) are used to derive range of obtainable capacity factors (18 to 37%) for medium-scale installed turbines. The proposed method is expected to provide accurate projections of logarithmic wind power law and achievable turbine efficiency in potential wind centres of Bangladesh.

KeywordsWind Shear, Profile Coefficient, Surface Roughness, Capacity Factor.

1. Introduction

In the field of renewable power generation, wind turbines have seen dramatic changes in technology and deployment over the last decade [1], [2]. The European Energy Association cites it as the fastest growing sector utilizing renewable energy [3]. This improvement of technology is accompanied with rapid increase in effective capacity and axle altitude of commercial turbines. The hub-height of hybrid (grid-supported) wind farms has reached the range of 50 up to 120m with a rotor span covering a radius varying from 40 to 80m [4]. In this situation, direct measurement of wind profile at heights occupied by commercial turbines has become more difficult in the absence of tall monitoring stations. But, accurate turbulence and wind speed statistics are necessary prerequisites for planning of efficient wind projects to be integrated in the national grid [1]. Estimation of wind shear characteristics can be a helpful tool for this problem as it can contribute in the forecasting of wind profiles in the lower atmospheric surface layer (up to 100m from ground level) [5], [6]. Although, a long observation period will be needed to make accurate projections of wind data when measured readings are only available from low altitude (10-20m) anemometers [7].

To boost the struggling rural power industry of Bangladesh, a developing country of South Asia, its national power development board (BPDB) has been concentrating new investments specifically on projects involving renewable resources [8]. This becomes even more important in light of the fact that, projected gap between generation and demand of electricity in Bangladesh can reach a peak of 2000MW during summer months, when extra supplies are required to drive pump-driven irrigation systems for the country's agricultural sector [9]. The concerned authorities have given priority to rural electrification by integrating solar and wind projects with existing grid-based systems in remote regions [10]. BPDB has sponsored fifty 20kW stand-alone turbines in the off-shore island of Kutubdia and initiated funding of a 200MW project to be built on the coastal region of Chittagong [11], [12]. However, lack of infrastructural development has led the average height of weather stations run by the BMD (the national meteorological department) to be only 12m. So, tower measurements have to be interpolated to higher hub-elevations to obtain readings necessary for power generation forecasting.

Because of the logarithmic nature of wind profiles in the lower stratum of planetary atmosphere, surface roughness is an important parameter for predicting wind speeds in the first 100 meters from ground level [13]. As detailed analysis of topographic features and local geographic anomalies and obstacles are needed to analyze this parameter, its accurate empirical values are not available for most locations of Bangladesh. Therefore, if a wind shear model can predict surface roughness from low- altitude data, it would prove beneficial for the country's wind profile forecasting. Wind shear data are also a prerequisite for derivation of capacity factor, another valuable tool for determining the design speeds of an installed turbine. It also helps to evaluate the maximum achievable turbine efficiency for a particular location [14]. This paper aims to propose a model to forecast surface roughness (in terms of roughness length) for UN (United Nations) selected potential windy regions of Bangladesh using wind shear characteristics and wind power profile law. It also exploits the roughness data to extract capacity factors for the locations and determines the relation between design speeds and achievable efficacy of commercial turbines. The derived results are compared against local geography to verify the accuracy of the proposed mathematical model. The findings are applicable for HAWT (horizontal axis) type turbines (0.2-2.5MW) of 20-48m blade length, 50-90m hub height and 8-14m/s rated speed.

The paper is structured as follows. In section 2, the process of collecting sample meteorological data for the entire country is explained on the basis of a UN survey. Section 3 derives the wind shear characteristics with time-series variation and establishes the probability distribution of shear factors. In section 4, curve fitting is employed to derive approximate surface roughness for the selected stations and finally, capacity factors are established in section 5 through the proposed method.

2. Sample Meteorological Data

Six weather stations are selected for this study from three diversely located and geographically important sectors of Bangladesh. On the basis of a survey undertaken by the environmental programme of the United Nations (UN), three potential regions are identified which have relatively stronger wind streams available on site. The survey program is called Solar and Wind Energy Resource Assessment Project (SWERA) and it identifies the strongest winds in the coastal belt of Bangladesh located on the South-Southeast border (sector-1) [15]. Two other hotspots (sector-2 and 3) are identified in the Southern and North-western inland regions. Wind data for these regions are collected from the database of the Bangladesh Meteorological Department [16] for a ten year period ('98-'07). It includes daily and monthly recordings of anemometer (hemispherical cup type, tolerance of 1.5%) readings with prominent wind directions at an average height of 12m. A second data set obtained with projections is collected at a higher altitude (30m). A total number of six stations are analyzed (two from each sector) including Cox's Bazar (21.43N 91.93E, coastal sector-1), Hatya (22.43N 91.1E, coastal sector-1), Khepupara (21.98N 90.23E, southern inland sector-2), Barisal (22.75N 90.33E, southern inland sector-2), Saidpur (25.78N 88.88E, north-western sector-3) and Rangpur (25.73N 89.23E, north-western sector-3).

3. Derivation of Wind Shear Characteristics

Wind shear is typically defined as a factor which determines the shape of the vertical wind profile in the lower stratum of the atmosphericsurface layer (ASL). It provides useful information which can be utilized to estimate wind profiles in the altitude range occupied by commercial turbine hubs, if directly measured meteorological data are not available for study [17].

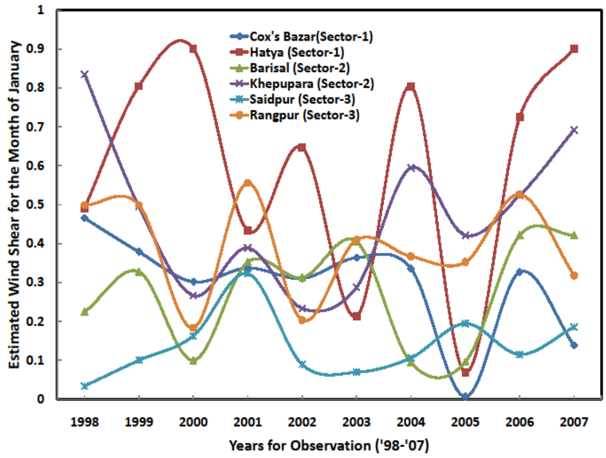


Fig. 1. Yearly variation of estimated wind shear for the month of January

The primary parameter identifying wind shear for a particular geographic location is the shear exponent ψ, which is related with available flow velocity measured at two different heights within the planetary boundary layer:

$$\frac{U_{z.hi}}{U_{z.lo}} = \left(\frac{Z_{hi}}{Z_{lo}}\right)^{\psi}, \quad (1)$$

where $U_{z.hi}$ and $U_{z.lo}$ are corresponding velocity readings for turbine heights Z_{hi} and Z_{lo}, respectively. An empirical formula like the 1/7th power law assumes a constant factor (=0.143) for the shear exponent which does not depend on geographical features of the monitoring station and ambient atmospheric condition. But, if the coefficient is derived from recorded data, it manifests variations on a diurnal and annual basis and indicates the necessity of studying the wind shear characteristics of a potential turbine site. After readings for the shear exponent are collected for a sufficiently long interval, a reliable estimation of a site-dependent shear coefficient will be possible, which can be employed to forecast the profile for altitudes where meter readings are not available [18]. In Bangladesh, data sampled by the national meteorological services is available for near ground level (anemometer towers have an average height of Z_{lo} =12m). With readings of wind velocity ($U_{z.hi}$) established at a higher elevation (30-50m), the shear coefficient ψ can be characterized with the logarithmic relation.

$$\psi = \frac{\log(U_{z.hi}/U_{z.lo})}{\log(Z_{hi}/Z_{lo})}, \quad (2)$$

In the following section, we study variation of the shear exponent over a ten-year observation interval in the selected monitoring sites.

3.1. Annual variation of wind shear

In the absence of hourly recording of anemometer readings in the weather stations, a reasonable first step will be estimating the annual pattern of extracted wind shear (ψ). To meet that objective, base readings are collected by tower mounted measurement devices around 12m and a 30m reading of projected wind velocities is used. Average readings are tabulated for the individual months (over a ten year period) and Fig. 1 presents estimated annual pattern of wind shear (ψ) for the month of January for six selected stations. The variability and the intermittency of wind gusts over this prolonged observation period is evident in the random variation of shear coefficients in this figure. For sector-1 (Cox's Bazar and Hatya), ψ randomly fluctuates between approximate figures of 0.1 and 0.8 over the ten year period. For sector-2 (Barisal) and 3 (Saidpur, Rangpur) the derived range of variation resides in the domains of 0.1-0.4 and 0.1-0.56. Hatya in sector-1 shows the largest degree of deviation. January is historically considered as a time of weak wind streams across the delta of the Bay of Bengal. But, when the curves are plotted in Fig. 2 for the month of September (when stronger wind flows are expected), the random pattern continues suggesting lack of suitability of annual shear variation for averaging wind shear characteristics.

3.2. Monthly distribution of shear coefficients

As distribution of wind profile is related with seasonal variation and climatological factors, it is expected that monthly distribution of shear coefficients in Fig. 3 will accurately reflect the seasonal ebbs and flows of available wind speeds in Bangladesh. The ψ factor peaks around the months of January and November when recorded for the ten year interval.

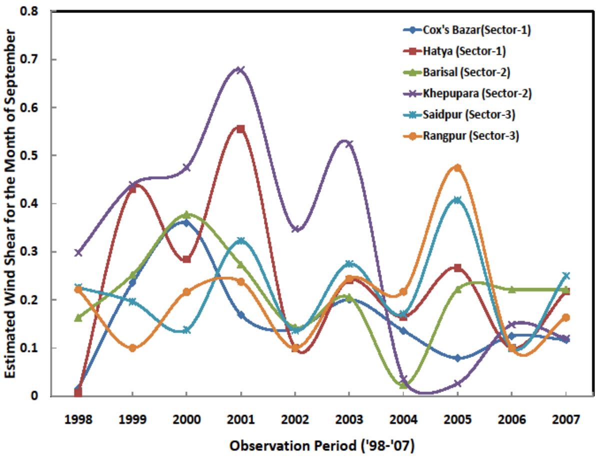


Fig. 2. Fall (September) pattern of forecasted annual shear factor

For the six stations, the curves follow roughly a similar pattern showing dips around the months of March, May and October. This may be explained by the fact that for slow moving months (like January) the difference between tower data and projected 30m wind speeds is on the higher side. Table I presents the estimated average shear factors (ψ, from monthly distribution) for the stations along with mean standard deviation obtained from monthly recordings. These average shear coefficients will be employed later to derive the value of the surface length applicable to the terrain of a particular weather station. So, when diurnal (hourly) recording of wind speeds is not available, monthly distribution of the shear factor can play a useful role for extracting power profile law coefficients for a wind turbine site.

3.3. Probability of Occurrence from Profile Distribution

The distribution of possible values for the shear factor (ψ) is presented in two groups in Fig. 4(a) and 4(b) respectively, showing the percentage probability of the shear exponent assuming a particular limit. The *pdf* (probability distribution functions) of the first three stations (Cox's Bazar, Hatya and Barisal) in Fig. 4(a) are consistent with the readings in Table I. The average (estimated) ψ factors for the three locations according to shear distribution are 0.162, 0.242 and 0.31, respectively. In Cox's Bazar (sector-1), local shear factor has a 58% chance of having the value of 0.1 and the probability is reduced to 25% for a higher value (0.3).

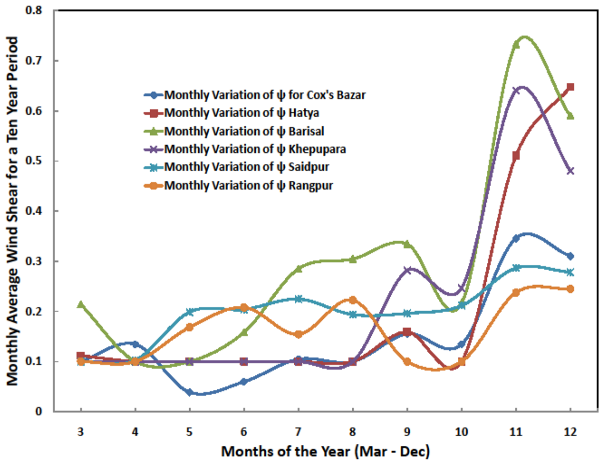


Fig. 3. A more regular monthly pattern of estimated shear factors

For Barisal (sector-2), the curve is more widely distributed with peaks at 0.3 and 0.65. Fig. 4(b) predicts that, for the second group of selected sites (Khepupara, Saidpur and Rangpur), projected average shear coefficients will approach 0.25, 0.184 and 0.18, respectively. In this figure, the probability bandwidth for sector-3 (Saidpur and Rangpur) is narrower than that of Khepupara. These extracted factors can be employed by the wind power profile rule to forecast available wind velocity (V_{tur}) in the 30-120m turbine (h_{tur}) range. The appropriate expression for the power profile will have the form

$$V_{tur} = V_{anem} * (\frac{H_{tur}}{H_{anem}})^{\psi}. \quad (3)$$

where V_{anem} is measured speed collected from an anemometer at an average height of hanem (≈12m for the stations of Bangladesh).

Table 1. Location of representative weather stations in Bangladesh and their estimated average shear factors

BMD Weather Center	Latitude	Longitude	Mean ψ	Std.Deviation
Saidpur (Sec.-3)	25.78N	88.88E	0.1846	0.0629
Rangpur (Sec.-3)	25.73N	89.23E	0.1867	0.0807
Barisal (Sec.-2)	22.75N	90.33E	0.3135	0.1813
Khepupara (Sec.-2)	21.98N	90.23E	0.2488	0.1798
Cox's Bazar (Sec.-1)	21.43N	91.93E	0.1617	0.0964
Hatya (Sec.-1)	22.43N	91.1E	0.2424	0.2065

4. Estimation of Surface Roughness

Wind shear characteristics are only useful for assessment of wind resources if wind power profile [5] is adopted as the basis of wind forecasting. To include the logarithmic variation of natural wind profiles in the atmospheric surface layer (30-120m), a secondary profile parameter called roughness length (e_o) has to be incorporated in the estimation process.

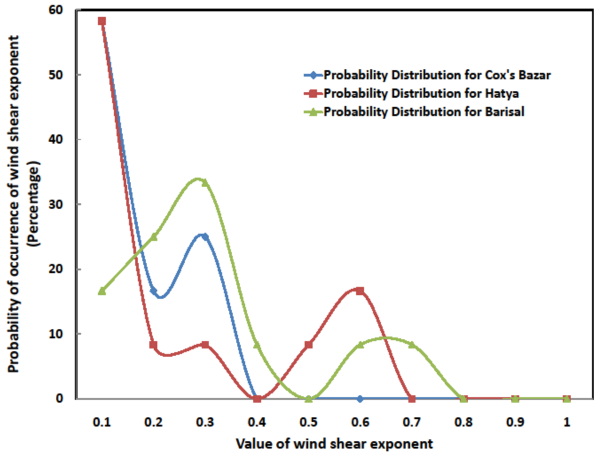
This parameter also measures the abrasive nature of the surface under observation. If precise topographic data are not readily available for a weather station, then selecting an appropriate value for e_o poses a significant design problem. On the basis of empirical observations, it is approximated by 0.0002 over water bodies, 0.03 for cultivated grasslands, 0.1-0.25 for low canopy areas and 0.5 for forest lands and housing estates [19]. A more accurate specification of the parameter will be desirable if a logarithmic law is put into use for profile forecasting [20], and the expression of estimated velocity $v(z_{tur})$ is written as a function of turbine elevation (z_{tur}) and measured meter speed (v_{ref}) at reference height (e_{ref}):

$$v(z_{tur}) = \frac{v_{ref}\log(z_{tur}/e_o)}{\log(e_{ref}/e_o)}, \qquad (4)$$

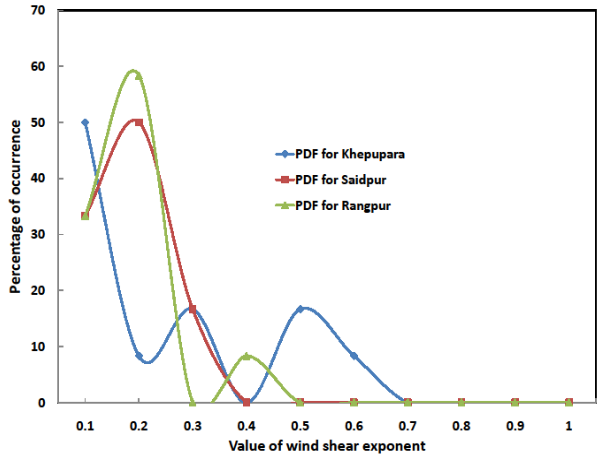
The e_o parameter is also necessary for derivation of wind power density (in watt/m^2) as the projection of WPD at a higher altitude (WPD_{tur}) is calculated from the relation

$$WPD_{tur} = [\frac{\ln(h_{tur}/e_o)}{\ln(h_{anem}/e_o)}]^3 * WPD_{ref}, \qquad (5)$$

where WPD_{ref} is the power density of wind at reference elevation [21]. So, a first step of an efficient way of deriving the surface length eo will be plotting wind profiles according to equation (3) for different possible wind shear exponents (ψ=0.1~0.5). The monthly distribution of wind shear characteristics will be able to provide a reading of average wind shear (see Table 1) for a particular station. As specific value of e_o is an unknown for a station, the next step will involve using equation (4) to derive logarithmic profiles with a permissible set of values for roughness length.



(a)



(b)

Fig. 4. a) Probability of occurrence of wind shear exponents for the selected stations b) Probability of occurrence of wind shear (contd.)

Consistency of the two sets of curves (obtained by power law and logarithmic profile) will indicate a pragmatic reading of roughness length which will be applicable for that particular station. In this process, surface roughness (e_o) was derived for three sample monitoring sites in the potential hot-zones of Bangladesh. Fig. 5 outlines the case for the station of Cox's Bazar in sector-1.

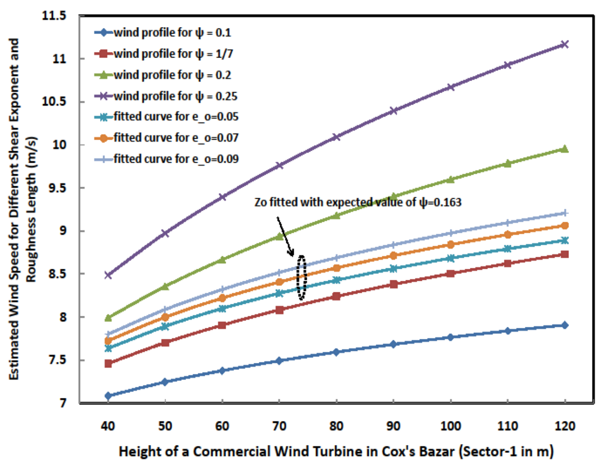


Fig.5. Estimation of surface roughness for Cox's Bazar (sector-1) at commercial turbine height

The figure plots power law profiles with the set ψ= {0.1, 1/7, 0.2, 0.25}.As average wind shear (ψ) for this particular site resides in the vicinity of 0.163, a best fitted logarithmic profile indicates that nature of terrain in this station is consistent with 0.07 as a value of eo. Investigation of the topography of the monitoring site in Cox's Bazar indicates existence of open grasslands and sparse vegetation in the area. So, an approximated empirical value for eo would have closely followed the curve fitted value of the proposed process [19].

Similarly, Fig. 6 and 7 derive surface roughness for stations from two other hot-zones of Bangladesh. The expected powerprofile coefficients (ψ) for Khepupara (sector-2) and Saidpur (sector-3) are 0.25 and 0.18, respectively, consistent with logarithmic projections obtained with e_o={~0.5, 0.15}. Topographic readings reveal existence of thick vegetation for Khepupara and low canopy areas for the station in Saidpur, again consistent with projected roughness readings. It also indicates that, error in prediction will increase for higher values of estimated shear factor (ψ). So, without burdensome statistical manipulation of geographic data [22], the outlined process is able to derive a relatively accurate estimation of surface roughness applicable for a weather monitoring site.

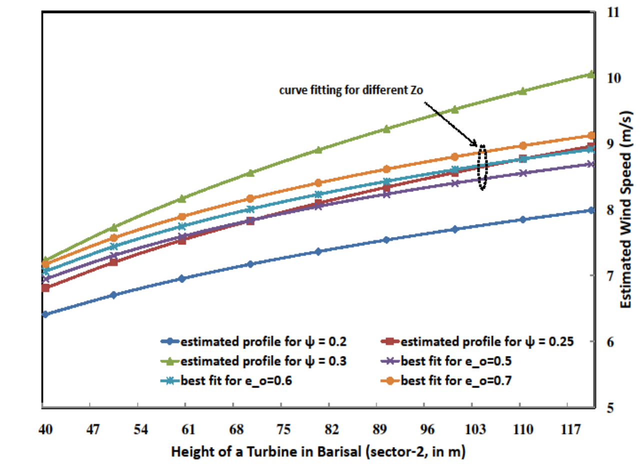


Fig. 6. Derivation of roughness length for Khepupara (sector-2)

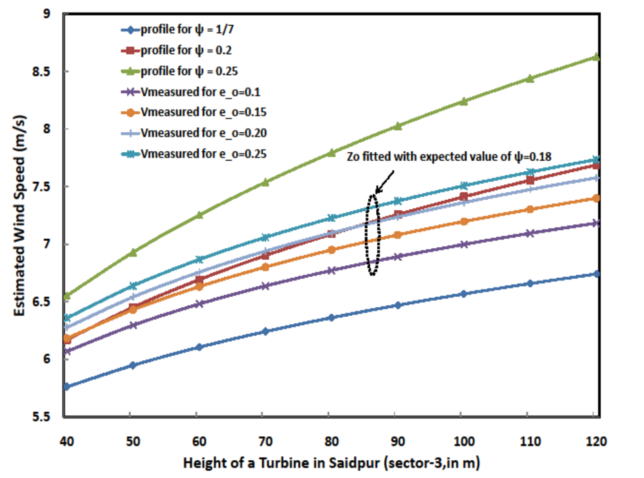


Fig. 7. Roughness fitting for Saidpur (sector-3) from projected curves

5. Estimation of Surface Roughness

5.1. Definition and distribution of capacity factor

Another important turbine parameter that can be extracted from wind shear characteristics is the capacity factor (CF) of a wind farm. For a power system, capacity factor is defined as the ratio of the effective available power output from the power generator to the nameplate capacity of the plant for a complete cycle of system operation. A base load electrical power plant is known to be capable of running at relatively high capacity factors (up to 90%) when CF is derived for a period longer than one month.Because of the intermittent nature of wind energy, CF for a commercial wind turbine typically resides in the range of 20 to 40% [23]. The geographic location of the wind farm plays an important part in the maximum achievable CF, as onshore wind mills typically have a 10% advantage over their off-shore counterparts.To define capacity factor in terms of estimated wind shear, it is necessary to define three design speeds for a particular weather station. Before that, the first design step will be forecasting the average wind profile at a commercial height using equation (4).For this study, capacity factor is derived at an altitude of 50m and the average profile is denoted with the notation Vavg.z=50m. If the design velocities [24] are designated as cut-in speed (Vcut.in), rated speed (Vrated) and furling velocity (Vfurling), then they are related with the average profile through the following equations:

$$V_{cut-in} = (0.6 \sim 0.7) * V_{avg.z=50m}, \tag{6}$$

$$V_{rated} = (1.5 \sim 2.0) * V_{avg.z=50}, \tag{7}$$

$$V_{furling} \geq 3 * V_{avg.z=50m}. \tag{8}$$

Among the design velocities, the turbine starts generating nominal power when the laminar flow exceeds a minimum limit (cut-in speed, $V_{cut.in}$). Up to the rated wind speed (V_{rated}), power output increases in a quasi-linear fashion and ultimately achieves the rated power (Prated). And furling velocity or cut-out speed ($V_{furling}$) indicates the threshold at which shut down occurs for the turbine [25]. Estimation of these design speeds requires derivation of probability density functions (*pdf*) of wind velocity for the sites. This *pdf* is termed with Weibull distribution [26] and is expressed with

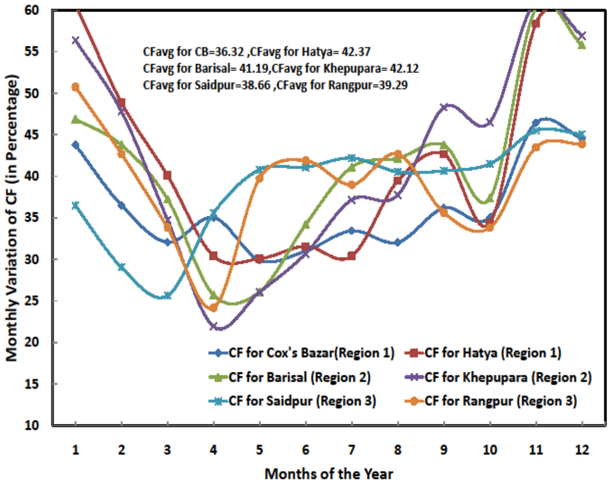
$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right] (k > 0, v > 0, c > 1), \tag{9}$$

where v is measured wind velocity at the turbine height, k is a site-dependent Weibull shape parameter and c is a Weibull scale parameter. The shape parameter (k) measures trend of the *pdf* curves and its value can be calculated from a curve representing the ratio σ/v [27]. The scale parameter (c), on the other hand, is related with average wind statistics. The value of k and c are expressed by

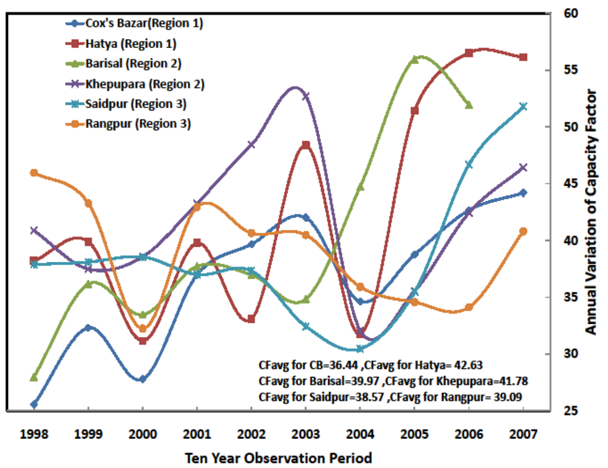
$$k = \left(\frac{\sigma}{v}\right)^{-1.086}, (1 \leq k \leq 10) \tag{10}$$

$$c = \bar{v}/\Gamma(1+\frac{1}{k}), \qquad (11)$$

where v and σ stand for mean wind velocity and its standard deviation respectively, and $\Gamma()$ represents an approximation of the first order gamma function:



(a)



(b)

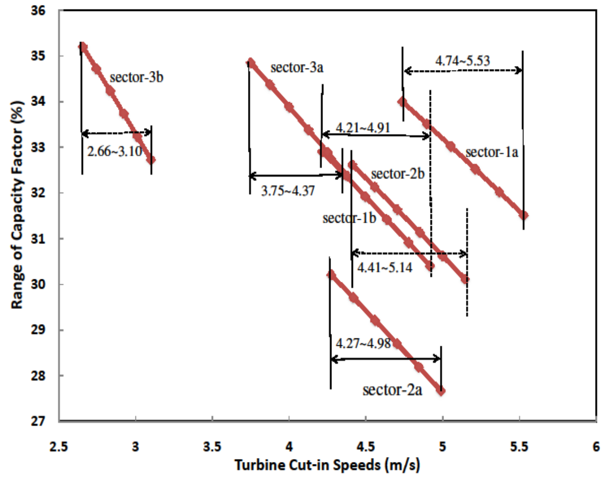
Fig. 8. a) Monthly distribution of achievable capacity factors (CF) at a height of 50m b) Yearly distribution of CF at weather points.

$$\Gamma(1+\frac{1}{k}) = 0.825 + 0.0135k + \exp[-(2+3(k-1))]. \qquad (12)$$

Based on the studies conducted in [27] and [28], best empirical value for the shape parameter can be taken as two and the scale parameter (c) is calculated for the six stations using base and estimated wind profiles. On the basis of the derived values, the final definition of the capacitor factor takes a fractional exponential form

$$CF = \frac{\exp^{\{-(\frac{v_{cut-in}}{c})^k\}} - \exp^{\{-(\frac{v_{rated}}{c})^k\}}}{(\frac{v_{rated}}{c})^k - (\frac{v_{cut-in}}{c})^k} - \exp^{\{-(\frac{v_{furling}}{c})^k\}}. \qquad (13)$$

As was evident from Fig. 1 and 2, there was no consistency in the shear coefficients (ψ) derived from annual wind profiles. But in case of capacity factors, when corresponding time-series models are projected for the six weather stations with ten-year and average-monthly calculations in Fig. 8(a) and 8(b), the average capacity factor for a site (indicated in the figures) remains consistent during both scenarios.



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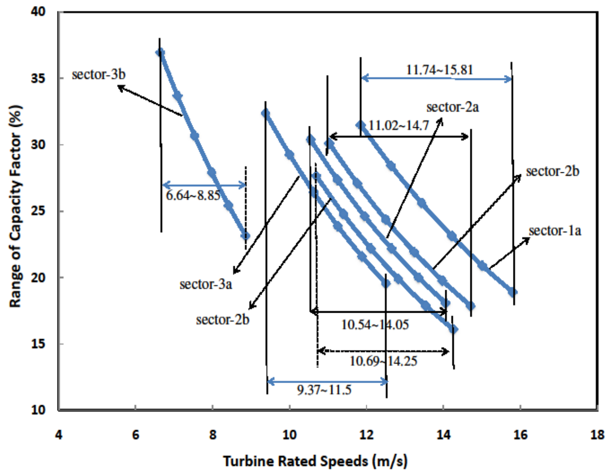

(b)

Fig. 9. a) Range of turbine cut-in speeds and corresponding capacity factors b) relation of capacity factors with turbine rated speeds

In this calculation, the lower limits of equations (6) to (8) are set as the design speeds satisfying a conservative restriction. So, these figures give a relatively higher estimate for the sites which will go down when the entire observation period and design criteria are factored in (as shown in the next section). The figures suggest that Hatya and Khepupara have the highest mean instantaneous capacity factors (42 and 41%, respectively) and range of fluctuation for the instantaneous factor covers 20-60% over the country.

5.2. Dependence of Capacity Factor on Cut-in and Rated Turbine Speeds

The significance of the design speed formulae is that the three design speeds for the wind turbine may reside within a certain range which will depend on ambient and seasonal factors and ultimately influence achievable capacity factors for the turbine. Mechanical and structural considerations also play a role in setting these speeds. So, it is important to observe the coverage of capacity factors for all feasible values of design speeds. To meet this objective, the roughness parameters (e_o, which were derived in the previous section) are employed to estimate the turbine speed at 50m ($V_{avg.z}$=50m) for a potential location. Fig. 9(a) and 9(b) depict the variation of estimated capacity factors for the weather points under observation against derived range of turbine cut-in and rated speeds. In the figures, the six stations are denoted by their corresponding sectors. Fig. 9(a) indicates that, despite having the same coverage of cut-in speed, achievable capacity factors can be significantly different for weather stations. Three stations have similar cut-in speeds covering from 4.21 to 5.14m/s but their capacity factors may vary by as much as 3%. The station at sector-3b (Rangpur) achieves moderate capacity factors (32.5-35.5%) even with lower wind profiles. On the other hand, station-1a (Cox's Bazar) manages a lower range (31-34%) with speed coverage of 4.74-5.53m/s. This indicates that profile parameters like the shape and scale factors (k and c) exert greater influence on achievable capacity factors than turbine design speeds. The curves in Fig. 9(b) are more closely clustered but cover a wider range of achieved capacity factors. Rated speed occupies between 6.64 to 15.81m/s and capacity factors have a range of 22 units between 16 and 38%. Both figures indicate that higher design speeds result in lower capacity factors for the wind turbine. So, careful optimization is required between the three speed categories to satisfy required load demand and necessary design efficiency for a potential wind power plant in these regions.

6. Conclusion

Roughness length is a crucial design parameter for a wind turbine location which is difficult to estimate from measured wind data. This paper proposes a novel empirical method to derive surface roughness from projected wind data with curve fitting. Wind power law is employed to identify seasonal and annual variation of site-specific wind shear factors and their average value is determined from probability histograms. In the absence of specific roughness data, roughness length is estimated (covering from 0.07 to 0.5) for potential turbine locations in Bangladesh which are consistent with geographic characteristics of the selected locations. The obtained values are put into use to forecast achievable wind-mill capacity factors (reaching up to about 40%) and their relation with turbine design speeds. It is found that an optimization process is necessary for turbine cut-in/rated speeds to maintain high capacity factors. This study is expected to assist installing of new wind turbines in UN selected weather points of Bangladesh.

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