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Reliable Estimation of Density Distribution in Potential Wind Power Sites of Bangladesh

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Abstract-This paper proposes reliable techniques for estimating density distribution (DD) of wind power on test-sites selected by the United Nations in Bangladesh. Wind power profile rule (with constant and variable power coefficients) and logarithmic law of wind shear are applied to seven unique methods used in forecasting wind power density achievable at commercial turbine-axle heights (30-120m). The problems related to fixating the power law coefficient against environmental and geographic factors are identified while predicting wind profiles from low-altitude (~10m) data. Relative deviations in forecasted density distribution are calculated to identify that, among the proposed methods, wind power rule with varying profile factors produce rates of inconsistency lower than 3% and a logarithmic method produces rates falling below 12% over a turbine range of 40-90m. Projected wind profiles in Bangladesh achieve a maximum power-class level of four and a power density coverage of 30-400 Watt/m^2, sufficient for medium scale (above 20kW) grid-supported wind projects.

Keywords: Density Distribution, Consistency of Prediction.

1. Introduction

Although hydro and solar systems have long been identified as the sustainable sectors among viable alternative resources [1, 2], recent trends have attempted to diversify planned developments of renewable energy in less-developed nations with inclusion of integrated wind power, biomass and geothermal energy projects [3-6]. Despite being located in the valley of Bay of Bengal with strong airstreams, lack of investments for grid-connected wind projects in Bangladesh has led to a situation where installed wind-turbines account for only 5% of the total share contributed by the country's renewable energy sector [7]. Initiatives to overcome under-utilization of this particular resource should be investigated as average power generation statistics in Bangladesh stood at 4900MW on July 2011 [8], falling roughly 10% short of the actual peak demand. Because of the inherent intermittent nature of wind farm outputs, surveys of estimated wind resources have long been established as a viable tool for assessing the possibility of using a particular location for installing commercial turbines [9, 10]. These surveys gain even more importance in weather stations where wind energy behaves like a fluctuating source of generation with a low capacity factor [11]. National weather service of a developing country like Bangladesh typically has limited monitoring stations with tower-mounted anemometers to observe meteorological patterns, directional distribution and vertical wind shear. Because these stations are not generally built to assess the possibility of integrating wind-turbines with conventional power generators, they often provide readings only in the lowest layer of the planetary boundary atmosphere (first 10-25m the troposphere) [12]. This is not a pragmatic range for operation of commercial turbines which will be able to generate sufficient backup to support a significant number of households with a low unit cost of electricity [13]. In this situation, variation of actual wind profile with altitude needs to be estimated, particularly at heights (over 40m) exploited by medium scale wind-turbines (50kW-2.5MW) to obtain an accurate projection of achievable power output generated by hybrid wind projects.

Published literature have reported a number of statistical parameters extracted from wind data to facilitate the process of predicting the capacity of an installed wind firm [14, 15]. Achievable wind shear (velocity curve) [16, 17], mean wind power density [18, 19], wind power classes [20] and frequency or directional histogram of cross-flow fluttering [21] have been verified as tools which could be used to analyze the prospect of harnessing energy from a windy spot. It is also desirable to establish consistent methods to accurately predict variation of instantaneous and long-term turbine parameters. In the absence of measured aerodynamic data at elevations above 30m in Bangladesh, this contribution aims to establish forecasting techniques which will be able to predict available wind power densities in the atmospheric surface layer (ASL) (30-120m) from raw data measured around a lower altitude. A number of schemes are employed to estimate the density profile for a particular location employing the wind power profile rule [9] and the natural logarithmic variation [22] of wind data. The problem of fixating the power law coefficient against roughness of surface, geographical properties and existence of significant obstacles is addressed by seven individual approaches. Their relative consistencies are judged by formulating deviation curves for six weather stations covering potential hotspots available in the country. The range of heights which is most likely to produce accurate forecasting is identified, which may assist future planning addressing integration of wind mills with ac-grid systems in remote areas of Bangladesh.

The following discussions are structured as follows. In section 2, we propose a methodology of selecting representative meteorological data from a group of 100 weather towers located in Bangladesh. Section 3 carries out prediction of density distribution (DD) over the lower ASL, first by fixating the empirical power law factor of wind profile and then by considering logarithmic pattern of projected wind shear. Deviation curves are derived to compare the relative consistency of different methods. In section 4, we explain a process to identify ranges of turbine height over which the proposed forecasting schemes will be able to predict in a reliable manner. Finally, the advantages of the proposed techniques are summarized along with their limitations which could arise from long-term uncertainties involved with wind power production.

2. Methodology of Collecting Meteorological Data

As the basis of the proposed forecasting methods in this paper, raw wind profile data collected from weather stations registered under the National Meteorological Department of Bangladesh (BMD) [23] are analyzed. The length of the observation interval is an important factor for wind profile forecasting which should sufficiently cover any multivariate dependency shown in historical wind data [11][13]. The influence of significant inter-yearly and short-term fluctuations present in recorded data should also be considered for base wind profiles obtained at a lower altitude. In this study, wind data are collected for a sufficiently long interval (ten year) as 12m wind shear, starting from 1998. Traditionally, assessment schemes which aim to evaluate potential of wind energy in Bangladesh have concentrated on the country's long southern coastal belt (a stretch of 500km) and offshore islands located in the Bay of Bengal [24][25]. But, a world- wide solar and wind energy assessment project (SWERA) undertaken by the United Nations in 2003 identified three sectors on the Bangladeshi mainland with relatively higher wind potential. It included the well-studied coastal zone and two landlocked sectors located in the south and the north-west [26]. The observations points in this study are diversely located at six weather stations over these three sectors. They are Patuakhali (22.33N 90.33E, southern inland sector-2), Barisal (22.75N 90.33E, southern inland sector-2), Cox's Bazar (21.43N 91.93E, coastal sector-1), Hatya (22.43N 91.1E, coastal sector-1), Saidpur (25.78N 88.88E, north-western sector-3) and Rangpur (25.73N 89.23E, north- western sector-3).

3. Estimation of Density Distribution

Historically, long-term planning of power projects in Bangladesh has not addressed the issue of integrating renewable supplies with the struggling grid-based ac power system existing in the country. This is evident in the fact that wind profile monitoring stations at commercial hub- heights (above 30m) are absent in locations of the country which have potential for running subsidiary stand-alone or grid-supported wind mills. Forecasting of wind shear by direct measurement can be made only with roof-mounted anemometers available at BMD observation stations. These stations are typically housed in two-storied facilities covering a mean elevation of 12m from sea level. In this situation, an assessment of the suitability of a particular location in terms of velocity profile (in m/s) and wind power density (WPD in watt/m2) can be made through projection of density distribution (DD). This is particularly useful for installing medium scale wind turbines (hub height: 40-120m) providing an average output of 50kW to 2MW (67hp-2.7khp). In the next section, wind shear above 30m is projected using the wind power profile rule (with a power law coefficient) from reference readings obtained around 12m for a stable atmospheric condition.

3.1. Empirical Formulae for Power Law Coefficient

The power law coefficient (ψ) is a factor which defines the wind profile in a particular area. It is influenced by presence of obstacles and meteorological stability parameters in the surrounding terrain and defined as a function of surface topography.

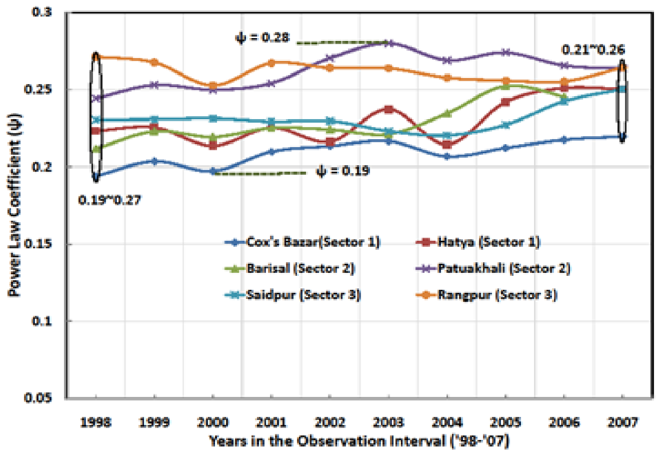

Fig. 1. Yearly variation of power coefficients as obtained by method 1

However, ψ is often assumed constant [24] under the assumption that variation of wind shear within the turbine coverage (40-120m, not including the span of rotor blade tips) is limited and predictable for a stable ambient condition without extreme weather elements. To justify the validity of the assumption of a constant ψ against elevation, measured profile readings at a number of altitudes are necessary [25] to monitor the pattern of the coefficient with the equation

$$\psi = \frac{\log(v_{tur}/v_{ref})}{\log(e_{tur}/e_{ref})}, \tag{1}$$

which suggests that establishing an empirical value for the exponent (ψ) is possible if anemometer wind velocity readings (v_{ref},v_{tur}) are available at reference elevation (e_{ref}) and turbine-axis altitude (e_{tur}). Even if ψ is fixated against height for a geographical site, its adopted value will still be a function of prominent geographical features and vary between the ranges of 0.1~0.5. Under a stable condition it will also depend on the shape of localized surface obstacles in the atmospheric surface layer. A number of published reports have used the one-by-seven power law [25, 27] for profile prediction where the empirical factor uses an universal value (1/7=0.143) in the planetary boundary layer (PBL). If wind readings from altering heights are not available in potential hot zones of a country then using equation (1) is not feasible and the constant ψ must be measured from a single anemometer reading (v_{ref}) [9] at e_{ref}=12m. An empirical expression for the projection of ψ which is supported by best fitted coefficients has the format

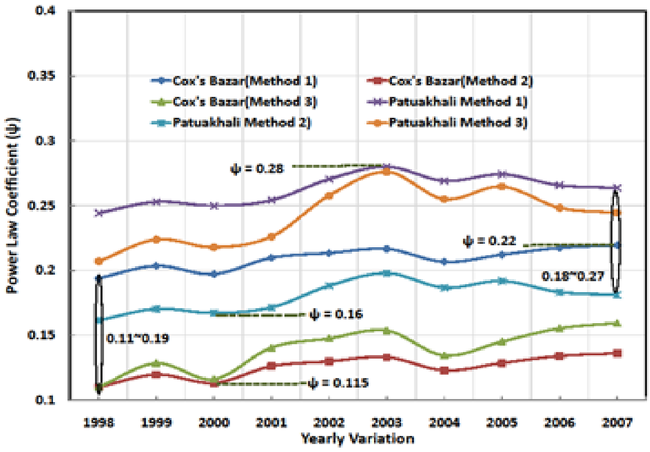

Fig. 2. Variation of ψ factor for the same location obtained from three empirical prediction techniques

$$\psi = \eta_0 + \eta_1 \ln(v_{ref}), \tag{2}$$

where η0 and η1 are observational constants obtained with curve fitting. considerations suggest that these constants must depend on particular topographic properties of a selected site. But reported studies have defined them as universal constants [28] with site-independent values of 0.37 and -0.0881 (*method 1*), respectively. For six selected weather monitoring outfits of Bangladesh, yearly variation of the power coefficient obtained from *method 1* is shown in Fig. 1 where the base factor value is not a constant but seems to vary within the range of 0.19~0.28. Because of the significant difference in the value of extracted power coefficients, it is difficult to define an empirically consistent universal power law factor for these stations (like 0.143 used in 1/7th power law). In this situation, a number of arguments have tried to readjust the universality of the statistical factors (η0 and η1) with additional sets of site-independent constants [9][10]. Two proposed examples which have tried to achieve empirical consistency use

$$\{\eta_0, \eta_1\} = \{.29, -0.09\}(method2) \text{ and} \tag{3}$$

$$\{\eta_0, \eta_1\} = \{.45, -0.17\}(method3). \tag{4}$$

Extracted average (yearly) ψ coefficients obtained from reference speeds (12m) using equations (3) and (4) are depicted in Fig. 2 for stations in Cox's Bazar and Patuakhali. The figure indicates a significant difference in the base (mean) values obtained by the three methods for the same location (0.215, 0.14 and 0.11 for Cox's Bazar, 0.26, 0.24 and 0.19 for Patuakhali). So no clusters can be observed among the curves in Fig. 2 while upper and lower limits for ψ stand at 0.115 and 0.28 along the y-axis. This is suggestive of inconsistencies in the notion of terrain-independent universal projection constants.

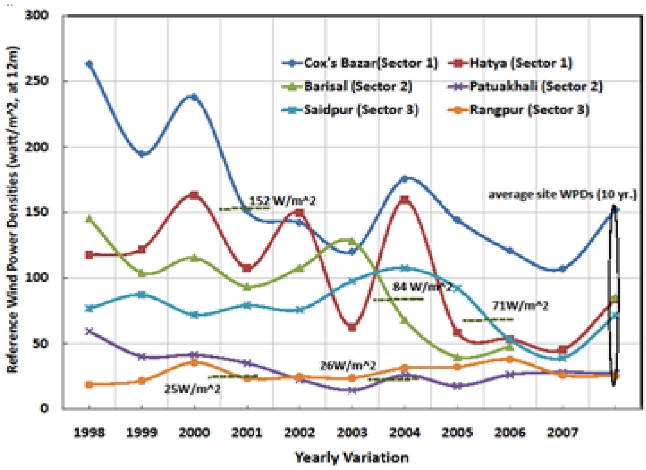

Fig. 3. Reference wind power densities (WPD_{ref}) at a height of e_{ref}=12m

3.2. Projection of Wind Power Density

As an estimation of energy output from a commercial turbine is often expressed in terms of wind power density (WPD, in watt/m^2), any inconsistency in wind profile forecasting with empirical equations should also be verified while making power density projections. Density Distribution (DD) is a good tool for assessing wind energy potential of a site because it does not depend on physical or geometric characteristics of the turbine assembly and is controlled only by ambient environmental factors. The analogue of the wind power profile law for WPD takes the form of the following equation

$$\frac{WPD_{tur}}{WPD_{ref}} = \left(\frac{e_{tur}}{e_{ref}}\right)^{3\psi}, \tag{5}$$

where WPD_{tur}/WPD_{ref} is the ratio of power densities of wind at turbine height and reference elevation, respectively.

Before embarking on WPD estimations with a power law variant, it is important to remember that density distribution (DD) can be calculated from recorded mean monthly readings of the wind profile (in m/s) or probability histogram of the wind speeds. Reference wind power densities (WPD_{ref}) calculated at a height of e_{ref} =12m are shown in Fig. 3 collected from the statistical equation

$$WPD = \frac{1}{2k}\sum_{y=1}^{k}(\phi_y V_y^{\ 3}), \tag{6}$$

where k is the size of a data set, φy is the air density measured on-site, and V_y denotes monthly wind speeds averaged over a period of ten years [20]. In Fig. 3, reference density is calculated for a particular station using twelve average monthly anemometer readings (k = 12 in equation (6) whereas φy is measured from elevation data (d) with the equation

$$\phi_y = 1.225 - (d * 1.194x10^{-4}) \tag{7}$$

As φy does not vary significantly over the monthly intervals it is considered independent of the suffix y in equation (5) and taken out of the summation formula while calculating reference density distribution (WPD_{ref}). Density of air, when defined as a function of elevation in Bangladesh, remain relatively true to the value of 1.22 kg/m^3 (highest elevation for the selected stations is 40m from sea level, for Cox's Bazar). The first three methods used in this study employ equation (5) where their differences are identified with the choice of the power law coefficient (ψ). Three sets of empirical constants (η0 and η1) define the ψ factors used by these methods and the ten-year average value of ψ is taken as a constant for a particular site to test its effect in generating inconsistencies during forecasting. Forecasted density distributions for three sample monitoring locations (Cox's Bazar, Patuakhali and Saidpur) are depicted in Fig. 4 using methods 1 and 2, showing significant difference in the predictions made with identical data for the same station. This difference increases with altitude and has a maximum ceiling of 290, 75 and 46 watt/m2 at an elevation of 120m for Cox's Bazar, Saidpur and Patuakhali, respectively.

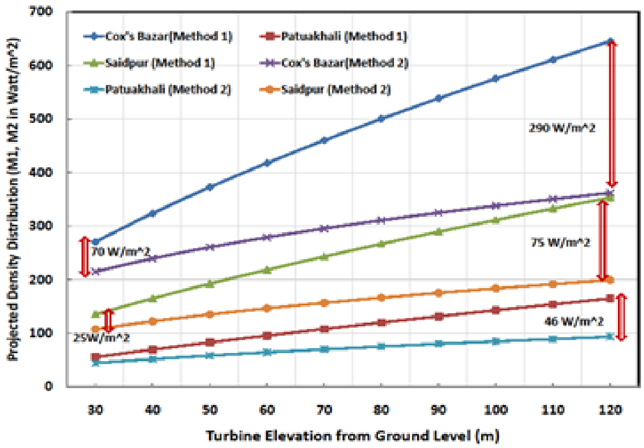

Fig. 4. Forecasted density distribution for three sample monitoring sites using methods 1 and 2

3.3. Deviation Curves for WPD

We employ the notation $D(x, y)e_{tur}$ to indicate the percent age difference in the predictions [29] made with methods x and y at the same height (e_{tur}) for a meteorological station and define it with

$$D(x,y)_{e_{tur}} = \frac{WPD(e_{tur})_x - WPD(e_{tur})_y}{WPD(e_{tur})_x}, \tag{8}$$

where $WPD(e_{tur})_{x/y}$ is an estimated WPD reading obtained from the method denoted in the subscript. The deviation curves calculated from the first three methods, when drawn for Cox's Bazar, Hatya, Rangpur and Patuakhali in Fig. 5, shows how the rate of inconsistency is greater than 14% in the entire altitude coverage except for D(1,3) obtained at Patuakhali and Rangpur. It would suggest that if the power law coefficient (ψ) is derived as a site-and-height independent factor using equation (2), it is likely to produce erroneous predictions of wind profile and density distributions manifested in Fig. 4 cannot be taken at face value.

3.4. Dependence of Power Law on Elevation

As the power law coefficient (ψ) cannot be defined accurately as a function of reference wind velocities obtained with roof-mounted anemometers, employing the wind power profile during prediction of wind power densities with equation (5) requires the ψ factor to be expressed in terms of altitude of turbine-axle and site-dependent parameters.

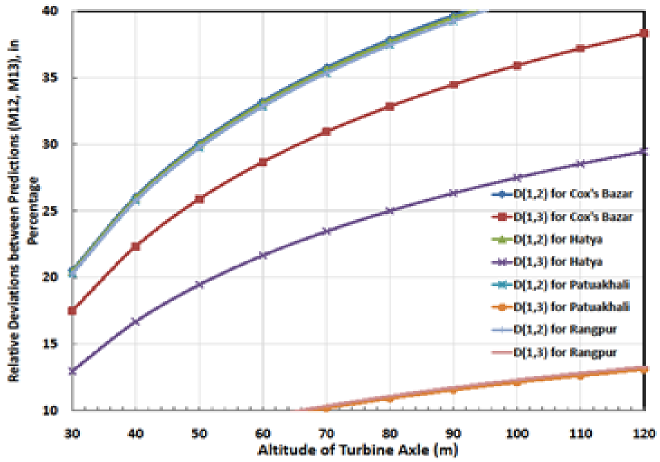

Fig. 5. Deviation curves calculated from the first three methods

To account for the logarithmic variation of vertical wind speed distributions in the atmospheric surface layer (first 100m from ground), an important corrective measure would be the inclusion of a roughness length parameter (e_o) in the calculation. This parameter assesses any effect of abrasiveness of the ground plane over which wind is circulating. It has been assumed in the previous section that near planetary boundaries (40-120m) the ψ exponent of the power profile does not vary and its specification depends on the local terrain. But, if turbulence or extreme weather conditions force this presumed constant to vary [30] in the

ASL, then ψ behaves as a function of roughness length (e_o) and altitude ztur with the relation

$$\psi = \frac{1}{\ln(z_{tur}/e_o)}. \tag{9}$$

This equation can also be assumed valid for a site with consistently strong winds. In the absence of precise topographic data for derivation of roughness length in Bangladesh, it is estimated with approximated factors (0.0002 for water bodies, 0.03 over open pastures, 0.1/0.2 for well vegetated areas and 0.5 for irregular landscapes with housing spreads) [31]. But if the profile of the ψ factor has to be established for an entire district covering urban, cultivated and hilly features then Table I indicates that increasing roughness raises the ψ factor and difference in the derived coefficient can be as high as 0.22 at low altitudes. This ceiling itself is greater than the value of the ψ factor (=0.1413) adopted in one-by-seventh power law.

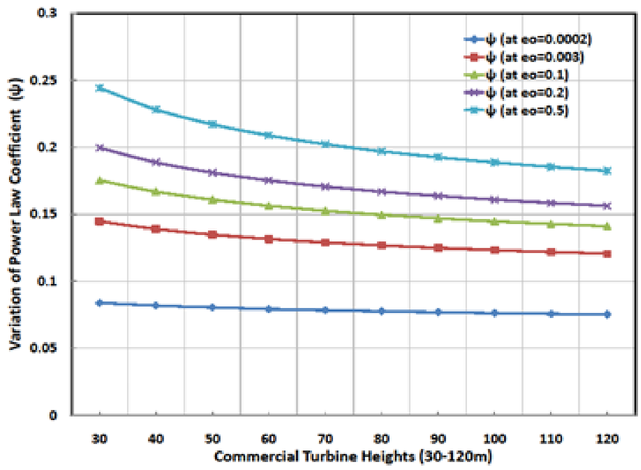

Fig. 6. Downward pattern of power coefficients when plotted against heights occupied by a commercial turbine

So depending on geography of the six specific stations supported by the Meteorological Department of Bangladesh, roughness length is considered as 0.03 for Cox's Bazar (proximity to sea beach), Barisal and Saidpur, 0.0002 for Hatya (surrounded by the Bay of Bengal) and does not enter in the equation because of the low speed profiles achieved in Patuakhali and Rangpur. Fig. 6 shows a regular downward pattern of the power coefficients when plotted against possible heights of a wind turbine. This pattern will only be valid for strong winds (>5m/s at 10m). So, a proposed fourth prediction method (*method 4*) using equation (5) takes the average of ψ (for e_0=0.03) in Barisal, Saidpur and Cox'x Bazar and uses the 1/7 *power law* for Rangpur and Patuakhali. Rather than directly estimating power densities from equation (5), a fifth method (*method 5*) uses the power profile rule to obtain wind shear (velocity profile) in the 30-120m range and uses equation (6) to project the distribution from the estimated wind speeds. Table II records specifications of the ψ parameter employed by *methods 4* and *5* against possible heights of a wind turbine (0.079 for Hatya, 0.130 for Barisal, Saidpur and Cox'x Bazar and 1/7 for Rangpur and Patuakhali).

Table 1. Influence of roughness length on the power law coefficient

e_o (no unit)	ψ (at 12m)	ψ (at 50m)	ψ (at 70m)	ψ (at 120m)
0.0002	0.0909	0.0805	0.0783	0.0752
0.03	0.1669	0.1348	0.1289	0.1206
0.1	0.2089	0.1609	0.1526	0.1410
0.2	0.2442	0.1811	0.1707	0.1563
0.25	0.2583	0.1887	0.1775	0.1620
0.5	0.3147	0.2171	0.2024	0.1825

3.5. Prediction of WPD with Variable Power Law Factor

Since deviation in the predictions manifested by D(*2, 4/5*), D(*1, 4/5*) and D(*4, 5*) still remains on the higher side (greater than 15%) around the critical height of 80m, a more accurate representation of the power profile rule is proposed with method 6 which regulates the power factor (ψ) as a function of z_{tur}. Forecasted wind densities obtained by this method are shown in Fig. 7 putting Cox's Bazar in the coastal belt on the top (reaching up to 350 watt/m^2) and pointing to two other clusters (Barisal, Saidpur with an average ceiling 150 watt/m^2 and Rangpur, Patuakhali achieving a base value of 50 watt/m^2). To verify the higher consistency achieved by method 6 its predictions are tested with a set of D(*5,6*) curves in the same plot. Error rate stays below 10% for an average coverage of the 30-75m for the four plotted stations and the trends rise almost linearly. The flat D(*5,6*) deviation profile achieved for Rangpur results from the use of 1/7th power law for low profile stations. Judging from these results, terrain dependent empirical standards (*methods 4* and *5*) and altitude-dependent power profile rule (*method6*) seem to share a greater range of consistency which is further enforced by a set of D(*4, 6*) tolerance curves drawn for four sample stations in Fig. 8. These curves manifest percentage deviation lower than 3% in an altitude range of 40-90m and lower than 1% over a height coverage of 60-80m occupied by medium-scale wind mills.

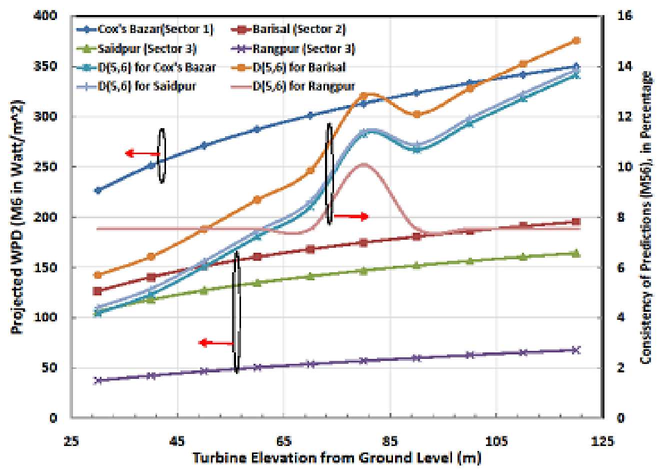

Fig. 7. Forecasted wind densities and deviation patterns from method 6

3.6. Logarithmic Forecasting of Power Density

A final forecasting method (*method 7*) is proposed on the platform of a logarithmic wind profile to estimate wind power density without exploiting a power law coefficient. The profile (velocity) equation for this standard at an elevation of z_{tur} includes the influence of aerodynamic ambience and is given by

$$u(z_{tur}) = \frac{u_{fr}}{\kappa}\ln(\frac{z_{tur}}{e_o}) + f(z_{tur}, e_o). \tag{10}$$

In this expression, whirling nature of gusts around the surface of an obstacle is factored in by including a parameter of friction velocity (u_{fr}) defined by roughness length (e_o) and Karman's constant (κ=0.41) [32]. The term $f(z_{tur},e_o)$ is a stability function depending on the Monin-Obukhov dimension (D) [33], nature of terrain, and elevation. This function, which can be derived empirically, describes effects of buoyancy on turbulent flow and has a fractional logarithmic definition:

$$f(z_{tur}, e_o) = -\frac{u_{fr}}{\kappa}\varepsilon(\frac{z_{tur}}{D}). \tag{11}$$

If average wind-drive speed at reference surface elevation (e_{ref} ≈12m) for the site is u_{tur}, then the expression for friction velocity [22] is defined with

$$u_{fr} = \frac{\kappa u_{tur}}{\ln(\frac{e_{ref}+e_o}{e_o})}, \tag{12}$$

and the secondary stability function $\varepsilon(z_{tur}/D)$ can follow a linear or exponential fit depending on the presence of turbulent elements in the environment [30]. Under an assumption of neutral stability, this function signifying steadiness satisfies the following expression

$$[1 - \frac{\varepsilon(z_{tur}/D)}{\ln(z_{tur}/e_o)}] \approx 1, \tag{13}$$

which ultimately makes the contribution of $\varepsilon(z_{tur}/D)$ insignificant, making it valid to assume

Table 2. Specifications of the ψ parameter against possible heights of a wind turbine

Altitude(Z)	Ψ (e_o=0.0002)	Ψ (e_o=0.03)	Ψ (e_o=0.1)	Ψ (e_o=0.2)
30	0.084	0.145	0.175	0.200
40	0.082	0.139	0.167	0.189
50	0.080	0.135	0.161	0.181
60	0.079	0.132	0.156	0.175
70	0.078	0.129	0.153	0.171
80	0.078	0.127	0.150	0.167
90	0.077	0.125	0.147	0.164
100	0.076	0.123	0.145	0.161
110	0.076	0.122	0.143	0.158
120	0.075	0.121	0.141	0.156
Avg.	0.079	0.130	0.154	0.172

$$f(z_{tur}/e_o) \approx 0. \tag{14}$$

If the discussed points concerning the stability function for a monitoring site hold true, then logarithmic density distribution (*LDD*) will be able to provide a conservative estimate of feasible wind power density. *LDD* also exploits roughness length to predict the distribution (WPD_{tur}) from reference densities without any power factor through the following equation

$$\frac{WPD_{tur}}{WPD_{ref}} = [\frac{\ln(z_{tur}/e_o)}{\ln(e_{ref}/e_o)}]^3. \tag{15}$$

The forecasted wind profiles for the selected stations obtained using this method are presented in Fig. 9. Here, difference in prediction between logarithmic law and power profile rule keeps below 10% when the turbine height is limited up to 80m. The deviation curve still shows a significant rate of error (reaching 35%) for a station like Rangpur with low wind potential. The two final *methods* (*6* and *7*) achieve identical patterns for predicted power profiles indicating a higher consistency achieved by these two methods. Hence, they may be employed together to estimate achievable wind power at a proposed site for a wind-mill during the phase of feasibility studies.

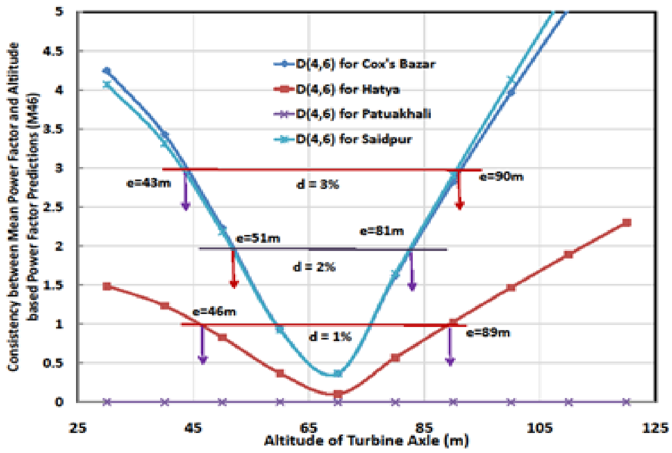

Fig. 8. Tolerance curves (D(4,6)) for four sample stations

4. Consistency Between the Methods

4.1. Relative Difference in Estimations

Out of the seven proposed methods discussed in this paper, the first three methods are strictly empirical using reference velocities obtained by direct readings of an anemometer near ground level (at an average height of 12m in Bangladesh). These schemes assume wind profiles to be independent of site and elevation and use constants extracted while fitting recorded data. As a result, they prove to be unreliable and produce variable results for the same weather station at identical heights. *Method 4* also employs a predefined power law coefficient over the range of observation (30-120m). But, this time, the factor is calculated considering the topography of the selected site and averaging its variation against turbine heights. The fifth method estimates wind power density in an indirect manner as it measures density distribution with weighted averages of estimated mean velocity and ambient wind density. The scheme which directly incorporates fluctuation of the power profile factor against altitude is *method 6*. Its comparison with the two previous schemes identifies the range of heights over which estimation error is likely to be minimized. To include an estimation technique which is independent of the shape of wind profile, a logarithmic scheme is listed as method 7 providing conservative estimates of achievable power density from surface roughness and reference velocities. Judging from the rate of deviation, three pairs (*methods 4-6, methods 5-6 and methods 6-7*) are deemed to be consistent leading to the conclusion that their dual employment is most likely to produce accurate forecasting of achievable wind potential in a country like Bangladesh.

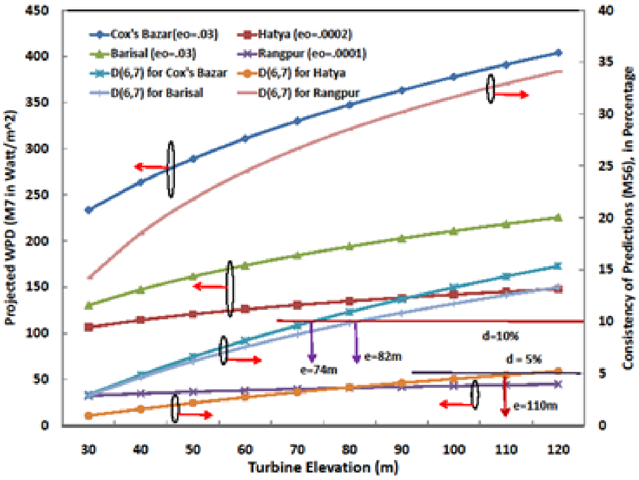

Fig. 9. Forecasted wind profiles and deviation patterns obtained from the logarithmic method (*method 7*)

4.2. Altitude Range for Reliable Prediction

A range of altitude for reliable prediction covers the heights of a turbine over which deviation of predicted density is likely to be minimum from actual data. A deviation curve, as defined in the previous section, would be an ideal tool to verify the existence of these ranges. The *D(4,6)* curves shown in Fig. 8 sample four selected stations with local minima which suggests a higher relative consistency between these two methods. Relative difference in predicted data stays below 3% in a domain of 43-90m with their lowest peaks occurring around 70m. Relative deviation denoted by *D(5,6)* increases against altitude, crosses the 10% limit around a turbine height of 70 and 75m in Fig. 7 and stays near a constant level of 8% for low profile stations. Higher gust velocity increases the likelihood of prediction error and may be responsible for the irregular peaks present on deviations curves in Fig. 7 (at or around 80m). The pair of logarithmic law and variable power profile rule produces consistent results with maximum relative deviation *D(6,7)* standing at 15.5%, 5.6% and 14%, respectively for sites in Cox's Bazar, Hatya and Barisal in Fig. 9. So, individual or joint application of *methods 5, 6* and *7* is expected to produce accurate estimations of wind power density when it comes to installing small to medium scale commercial wind turbines.

5. Conclusions

This paper attempts to devise an efficient method to estimate elevated wind power density in the planetary surface layer of selected potential hotspots (defined by the United Nations) in Bangladesh. Applying wind power profile rule and method of logarithmic profiling, seven unique forecasting techniques are tested on raw measured data collected around 10m. Wind shear (in terms of density distribution) is calculated in the 30-120m range in the absence of directly measured data. Relative deviation in estimated readings, which is lower than 5%, is achieved for 225kW-1MW turbines (with axles reaching 43-90m) with the proposed methods. Variation of power profile factor against surface roughness and turbine height are considered and three methods with higher prediction consistency for commercial turbines are identified. This study is expected to assist the assessment of wind-energy potential of Bangladesh and support feasibility studies to boost the fledgling hybrid wind-energy industry existing in the country.

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