Wind Energ. Sci. Discuss., https://doi.org/10.5194/wes-2018-16
Manuscript under review for journal Wind Energ. Sci.
Discussion started: 3 April 2018

Effect of Atmospheric Stability on the Wind Resource extrapolating models for large capacity Wind Turbines: A Comparative Analysis of Power Law, Log Law and Deaves and Harris model

[1]Pramod Kumar Sharma, [2]Vilas Warudkar, [3]Siraj Ahmed
[1]Research Scholar, Department of Mechanical Engineering, M.A.N.I.T, Bhopal [M.P] India
[2]Assistant Professor, Department of Mechanical Engineering, M.A.N.I.T, Bhopal [M.P] India
[3]Professor, Department of Mechanical Engineering, M.A.N.I.T, Bhopal [M.P] India
*Corresponding author: sharma786pramod@gmail.com
Telephone Number : +91 7554051611, +91 7554051616
Fax : +91 7552670562

Abstract

To observe accurate wind climate from the available met mast measured wind data at different heights an accurate wind shear model is necessary. Since WAsP and windPRO is software package which provide the better representation of wind profile over homogenous terrain only. Though, a separate module named as WAsP CFD has been added in both of the software to predict correct wind resource in complex terrain also. Now days terrain dependent wind resource model has been become a key issue for the researchers. Out of many wind extrapolating model such as PL (power law), LogL (log law), LogLL (Log linear law) and Deaves and Harris Model Log law was found to be better representation of wind profile. This study presents a comparative analysis of three different wind extrapolation models. Based on one year (2015-2017) wind data from met mast of 10min. interval at 10, 50, 80, 100 and102m, and the result was compared with the relation of atmospheric stability. The licensed version of WAsP and windPRO software was also used to calculate wind resource parameter such as roughness index and roughness class etc. RMSE and NRMSE was found to be least in case of log linear model which is 0.11 and 0.01784 respectively in compare to PL and Deaves and Harris models.

Keywords- ABL, LIDAR, Monin-Obukhov length, Richardson Number, WAsP, windPRO

Nomenclature

Abbreviations

WT	wind turbine
WAsP	Wind Resource Analysis and Application Programme
windPRO	Wind Energy Project Design and Planning
PL	Power law
LogL	Log linear law
ABL	Atmospheric Boundary Layer
MOST	Monin-Obukhov similarity theory
LogLL	log-linear law
MLM	Maximum likelihood method
MMLM	Modified Maximum likelihood method
Ri	Richardson number
CFD	Computational fluid dynamics
LIDAR	Light Detection and Ranging
PD	Panofsky and Dutton (PD) model

Variables

v	wind speed [m/s]
k	shape factor
c	size factor [m/s]
u*	friction velocity [m/s]
z_o	roughness length [m]
K	von Karman's constant (assuming 0.4)
L	Monin-Obukhuv length [m]
ρ	air density [kg/m^3]
C_p	specific heat at constant pressure
H	is sensible heat flux [k. m.s^{-1}]
T	temperature in Kelvin [k]
Φ_m	Monin-Obukhov stability function
α	wind shear exponent
v_g	geostropic wind speed [m/s]
h	atmospheric boundary layer height [m]
f	coriolis parameter [s^{-1}]

Statistical parameter

n	total number of measured /or calculated data
m	number of measured data
c	number of calculated data
μ_m	$\overline{m_i}$ mean of n measured values
σ_m	standard deviation of n measured values
μ_c	$\overline{c_i}$ mean of n calculated values
σ_c	standard deviation of n calculated values
RMSE	root mean square error

Wind Energ. Sci. Discuss., https://doi.org/10.5194/wes-2018-16
Manuscript under review for journal Wind Energ. Sci.
Discussion started: 3 April 2018

1. Introduction

2015 marks the end of the beginning for the low carbon economy. As per the report of REN21 Global Status Report (GSR) 2016, 173 countries across the world launched the target policy, 110 countries had in place either feed in policy. Accurate measurement of wind resource is necessary to erect any wind farm. Earlier method uses cup anemometer and wind Vane to measure the wind velocity and direction IEC. Due to advancement of Wind Power technology attention of researchers had turned to increase the hub height. To measure the wind data at more than 100 m height by using conventional method through met mast is now becoming the costly and time consuming process. (Henry W. Tieleman, 2008) compared the observations from power law, logarithmic law and Deaves and Harris model in terms of mean wind speed and turbulence intensity. At 10m height non neutral thermal stability affects the wind velocity profile and should not be neglected. (Daniel R. Drew et.al., 2013) found to be best fit non equilibrium deaves and harris wind speed profile model in urban areas. (Hideki Kikumoto et.al., 2017) investigated the accuracy of wind speed measurement using PL in low speed region. The results were compared and analyzed with Doplar Lidar and ultrasonic measured wind data in the urban boundary layer of Tokyo Japan. (Nicholas J. Cook, 1997) compared the wind speed profile with the power law and DH. The D&H model fitted the profile near the ground and top of the ABL due to satisfying the criteria of both boundary conditions. (Giovanni Gualtieri, Sauro Secci, 2011) compared and investigated the accuracy of prediction of wind speed over a flat and rough region at 10m and 50m height agl in which the role of atmospheric stability and surface roughness had discussed. (Giovanni Gualtieri, 2016) had investigated the time varying relation of wind exponent with atmospheric stability. The model was compared with PD and found to be finest and accurate approach in terms of wind speed profile and energy yield calculation in neutral conditions. A number of equilibrium wind speed model namely as PL, LogL and DH had been discussed by (Davenport, 1960; Simiu and Scanlan, 1996; Deaves and Harris, 1978). Panofsky and Dutton (1984) and Elliott (1958) studied the effect of inner boundary layer with a step change in surface roughness for the wind urban wind profile predictions. Deaves (1981) had utilized the concept for heterogeneous terrain and this was adapted into UK wind loading code also. (Giovanni Gualtieri, 2017) tested and compared the DH model with PL with all stability conditions. The DH model found to be best fitted and tuned and its accuracy seems to be increased with height from 80m to 140 agl. Due to increasing demand of energy, Wind resource prediction has become a crucial issue markedly for energy investors to accurately analyze the wind speed at different hub height of WT. This is very much necessary during the feasibility study to abate the cost of wind farm installation. There are many researchers who worked on different wind extrapolating models such as PL, LogL, LogLL and DH. Every model has its own significance and assumptions depending upon the type of terrain where wind speed has to be predicted. (Sharma et. al. 2014) had optimized 150m higher wind monitoring tower using ANSYS for Indian Condition. (Sharma et. al. 2014) Further the work had extended had discussed the incorporation of advance piezoelectric and nana composite material for hybrid offshore tower material.

2. Wind Profile extrapolating models

First time originally power law was proposed for the purpose of designing the wind load especially in structural engineering (Davenport, 1960). Due to simplicity of PL model which can be applied to larger height in compare to logarithmic law (Counihan, 1975) subjected to various terrain conditions. Following models had been generally adopted for the wind profile predictions under certain assumptions:

2.1 Deaves and Harris (D&H) model

This model was developed in two stages in strong wind conditions. In the first stage it was developed for the ABL in equilibrium over uniform roughness and in the second stage to account for multiple step changes in roughness. The model was further developed to different kind of heterogeneous terrain. UK, Australia and New Zealand had adapted this model into its wind design codes. If u_* is the friction velocity, k is the von karman constant (assumed 0.4), z_o is the roughness length, h is ABL height than velocity v has been define as:

The D&H model is also known as "logarithmic with parabolic defect" speed profile equation:

$$V = \frac{u_*}{k}\left[\ln\frac{z}{z_o} + 5.75\left(\frac{z}{h}\right) - 1.88\left(\frac{z}{h}\right)^2 - 1.33\left(\frac{z}{h}\right)^3 + 0.25\left(\frac{z}{h}\right)^4\right] \quad (1)$$

$$h = \frac{u_*}{6\,f} \quad (2)$$

where, f is the coriolis factor which depend on the site latitude angle. The extended model of D&H with step change in roughness had been given the concept of transition from outer and inner boundary layer. It is described as:

$$u_{*,inner} = u_{*,outer}\left[1 - \frac{\ln\left(\frac{z_{0,outer}}{z_{o,inner}}\right)}{0.42 + \ln m_o}\right] \quad (3)$$

$$m_0 = \frac{0.32\,X}{z_{o,inner}\;(\ln m_o - 1)} \quad (4)$$

X is the downward distance towards the change in surface roughness and m_o is the constant parameter.

As pet Similarity theory,

$$\frac{V}{u_*} \cong \frac{1}{k}\ln\left(\frac{z}{z_o}\right) \; when\; z \cong h \quad (5)$$

$$V \to V_G \; and \; \frac{dV}{dz} \to 0 \; as\; z \to h \quad (6)$$

V_G Stands for the geostrophic wind speed satisfies the criteria of upper and lower boundary conditions to the ABL. Geostrophic wind speed calculated when the thermal flux generated by the heat and friction are equal.

2.2 Log- Law model

The log law model was derived from Eq. (5) and holds over a ground surface:

$$V = \frac{u_*}{k}\ln\left(\frac{z}{z_o}\right) \quad (7)$$

It is clear from Eq. (7) that log law satisfies the lower boundary conditions only not the upper one. Typically it had been found to poor model for a height greater than 200m.

2.3 Power law model

Wind Energ. Sci. Discuss., https://doi.org/10.5194/wes-2018-16
Manuscript under review for journal Wind Energ. Sci.
Discussion started: 3 April 2018

The wind speed at a height z uses the empirical formula:

$$\frac{V}{V_{ref}} = \left(\frac{z}{z_{ref}}\right)^{\alpha} \tag{8}$$

V_{ref} to the wind speed at the height say z_{ref}. Power law indicates the increment of surface wind speed with respect to height z. The PL neither satisfies the upper boundary nor the lower boundary conditions. In compare to log law model it fits well for the wind speed profile at larger height, which is one of the critical reason for its preference. Though, it had not been recommended to use it very close to the ground. Most of the research matched well with the PL over the height value from 30m to 300m a.g.l. The value of α varies with respect to wind speed, height and surface roughness. In practice, the wind shear exponent α often assumed as equivalent to the aerodynamic roughness length z_o.

2.4 Estimation of Monin-Obukhov length

The turbulence within the surface boundary layer is defined by Monin- Obukhuv length scale L as:

$$L = -\frac{\rho\, C_p T u_*^{3}}{k.g.H} \tag{9}$$

where ρ stands for air density at temperature T, C_p is the specific heat at constant pressure, k is the Von Karman constant u_* is the friction velocity and H is the sensible heat flux. The Monin- Obukhuv length scale L can be calculated by computing the Bulk Richardson number which requires only single wind speed and temperature measurements at two heights. Gradient and bulk Richardson number can be defined as:

$$R_i = \frac{g\Delta z\Delta\theta}{\theta_1 \Delta u^2} \tag{10}$$

where $\Delta\theta = \theta_2-\theta_1$, $\Delta z= z_2- z_1$ and $\Delta u=u_2- u_1$ are the measured parameter at two height. When the temp. and wind speed measurement is available only at single height (Barker and Baxter, 1975)

$$R_{ib} = \frac{g z_2 \Delta\theta}{\theta_2\, u_2^{2}} \tag{11}$$

$$\varepsilon = \frac{\varphi_m^{2}}{\varphi_h} R_i \tag{12}$$

(Businger et.al., 1971) suggested

$\frac{\bar{z}}{L} = \varepsilon$, $\bar{z}$ stands for geometrical mean height of z_1 and z_2, and φ_m and φ_h are the non dimensional functions related to Wind shear and temperature gradient, as per (Dyer, 1974) φ_m *and* φ_h :

$$\varphi_m = \begin{cases} (1-\gamma\varepsilon)^{-\frac{1}{4}}, & \varepsilon<0 \\ (1+\beta\gamma), & \varepsilon\geq 0 \end{cases} \tag{13}$$

$$\varphi_h = \begin{cases} R(1-\acute{\gamma}\varepsilon)^{-\frac{1}{2}}, & \varepsilon<0 \\ (R+\beta'\gamma), & \varepsilon\geq 0 \end{cases} \tag{14}$$

(Binkowski, 1975) found the following results, the function based on two stability conditions

$$\varepsilon = \begin{cases} \frac{R_i}{R}\,(1-\acute{\gamma}R_i)^{\frac{1}{2}}/(1-\acute{\gamma}R_i)^{\frac{1}{2}} & R_i\leq 0\ ) \\ \dfrac{\frac{R_i}{R}}{1-\frac{R_i\beta^{2}}{\beta'}} & 0<\frac{R_i\beta^{2}}{\beta'}<1 \end{cases} \tag{15}$$

$$\bar{z} = \frac{z_1+z_2}{2}, \quad \bar{z} \text{ is the mean height} \tag{16}$$

$$\frac{z_2}{L} = \frac{kR_{ib}F^{2}}{G} \tag{17}$$

$$F = \frac{u}{u_*}\begin{cases} ln\left[\left(\frac{z_2}{z_o}\right)\left(\frac{\eta_o{}^2+1}{\eta_2{}^2+1}\right)\left(\frac{\eta_o+1}{\eta_2+1})^2\right)\right] + 2\ tan^{-1}\left(\frac{\eta_o-\eta_2}{1+\eta_o\eta_2}\right), & L\leq 0 \\ ln\left(\frac{z_2}{z_o}\right)+\frac{\beta z_2}{L}, & L\geq 0 \end{cases} \tag{18}$$

L depends upon two stability conditions

Wind Energ. Sci. Discuss., https://doi.org/10.5194/wes-2018-16
Manuscript under review for journal Wind Energ. Sci.
Discussion started: 3 April 2018

$$G = \frac{\Delta\theta\, u_*}{(-w'\theta')} = \begin{cases} R \ln\left[\left(\frac{z_2}{z_o}\right)\left(\frac{\lambda_1+1}{\lambda_2+1}\right)^2\right], & L \leq 0 \\ R\left[\ln\left(\frac{z_2}{z_o}\right) + \frac{\beta'(z_2-z_1)}{L}\right], & L \geq 0 \end{cases} \quad (19)$$

$$\eta_2 = (1-\gamma z_2/L)^{\frac{1}{4}} \quad (20)$$

$$\eta_o = (1-\gamma z_o/L)^{\frac{1}{4}} \quad (21)$$

$$\lambda_1 = (1-\gamma' z_1/L)^{\frac{1}{2}} \quad (22)$$

$$\lambda_2 = (1-\gamma' z_2/L)^{\frac{1}{2}} \quad (23)$$

Where η_2 η_o λ_1 λ_2 are the function of Monin- Obukhuv length L. G is the function of Richardson no. and mean gradient height z. F stands for logarithmic function of speed and friction velocity.

3. Observation and site details

Jamgodrani hills have a huge potential in terms of power production. The 100m mast is located in District Dewas at Jamgodrani Hills. The elevation of the mast location is 573m above mean sea level. Site coordinate has been converted into UTM (Universe Transverse Mercator) system to perform line and area roughness calculation purpose using WAsP and windPRO. There were five wind anemometers and wind vane had mounted on the mast to measure wind speed and direction respectively. To verify the Monin- Obukhuv Similarity theory two temperatures and one pressure sensor had also installed. Table 1 and Fig.1 shows the mast details and location respectively.

Table 1 Site Details

Site Coordinate	(E)Longitude- 76°09'2.50" (N) Latitude- 22°58' 58.20" UTM-2542426 N, 619480 E
Duration	2015 to 2017
Site name	Jamgodrani Hills
District	Dewas
State name	Madhya Pradesh
Mast Height	100m
Elevation	573mAMSL
Location of Anemometer	10m, 25m, 50m, 80m, 100m.
Location of Wind vane	10m, 25m, 50m, 80m, 100m
Location of Pressure sensors	2m, 10m
Location of temperature sensors	2m, 10m

Wind Energ. Sci. Discuss., https://doi.org/10.5194/wes-2018-16
Manuscript under review for journal Wind Energ. Sci.
Discussion started: 3 April 2018

WIND ENERGY SCIENCE DISCUSSIONS
Open Access
european academy of wind energy

Fig. 1 Met mast location (Source Google Earth)

Weibull parameter (k and c) was calculated by two different methods namely as MLM and MMLM. It is very much clear from the Table 3 in compare to Table 2 Weibull parameter are more than Table 2.

MLM is a widely accepted method to estimate the Weibull parameter. It requires more extensive mathematical calculations. In the first step k is calculated by using the following equation.

$$k = \left(\frac{\sum_{i=1}^{n} v_i^k \ln(v_i)}{\sum_{i=1}^{n} v_i^k} - \frac{\sum_{i=1}^{n} \ln(v_i)}{n}\right)^{-1} \tag{24}$$

$$c = \left(\frac{1}{n} \sum_{i=1}^{n} v_i^k\right)^{\frac{1}{k}} \tag{25}$$

n stands no of observation of zero wind speed and v_i i_{th} operation wind speed.

This method is similar to MLM and estimated by iteratively using the following two equations . It is used when wind data is available in frequency distribution form. If v_i is the wind speed related to bin i, $f(v_i)$ is the frequency range within the region of bin i, n is the total no of bins and $f(v >=0)$ is the probability of wind speed.

$$k = \left(\frac{\sum_{i=1}^{n} v_i^k \ln(v_i) f(v_i)}{\sum_{i=1}^{n} v_i^k f(v_i)} - \frac{\sum_{i=1}^{n} \ln(v_i)}{f(v \geq 0)}\right)^{-1} \tag{26}$$

$$c = \left(\frac{1}{f(v \geq 0)} \sum_{i=1}^{n} v_i^k\right)^{\frac{1}{k}} \tag{27}$$

Wind Energ. Sci. Discuss., https://doi.org/10.5194/wes-2018-16
Manuscript under review for journal Wind Energ. Sci.
Discussion started: 3 April 2018

Table 2 Weibull parameter by MLM

100m		80m		50m		10m	
k	c	k	c	k	c	k	c
2.24	7.131	2.219	6.70	2.3621	6.25	2.164	4.193

Table 3 Weibull parameter by MMLM

100m		80m		50m		10m	
k	c	k	c	k	c	k	c
2.431	7.67	2.42	7.24	2.57	6.78	2.45	4.736

*Roughness length=0.3183m, *Class= 2.8

4. Result & Discussion

Annual mean wind speed and Mean turbulence intensity is calculated at different heights from ground level. It is clear from Table 4 that the annual wind speed increase with respect height, but mean turbulence intensity decreases. Due to more predominate viscous and obstruction effect near the ground level wind turbulence is more. As the height from the ground increases wind becomes so smooth cause rapidly decrease in TU.

Table 4 Wind characteristics

AMWS (Annual Mean wind speed) in m/s				MEAN TURBULANE INTENISTY (TU)			
100m	80m	50m	10m	100m	80m	50m	10m
6.32	5.93	5.53	3.71	0.124	0.143	0.150	0.24

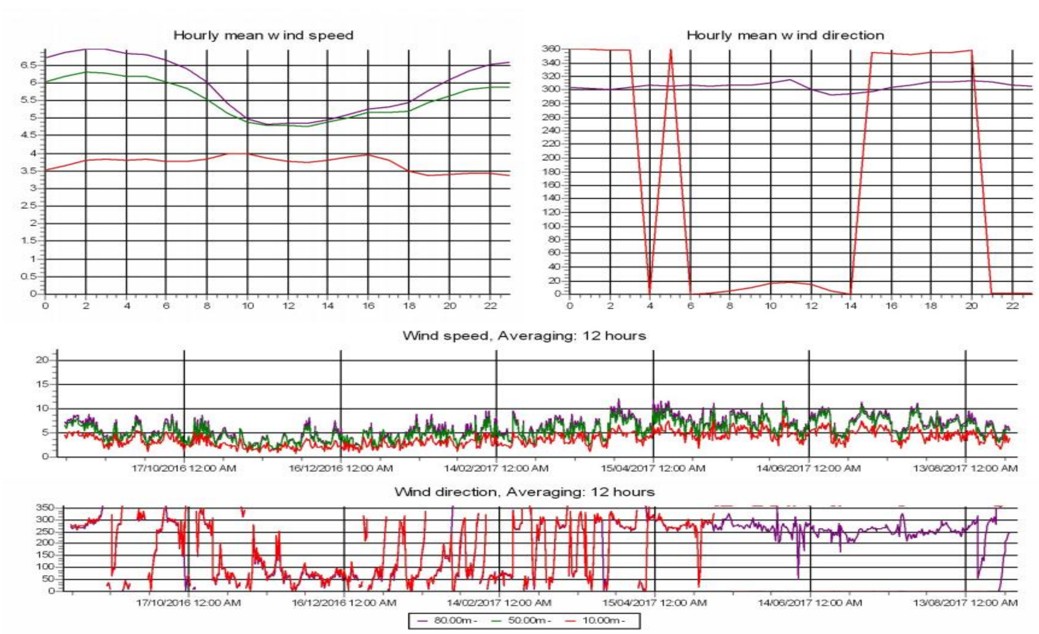

Fig. 2 Wind speed and direction variation

The hourly variation of wind speed and direction has been shown in Fig. 2 at 10m, 50m and 80m height respectively.

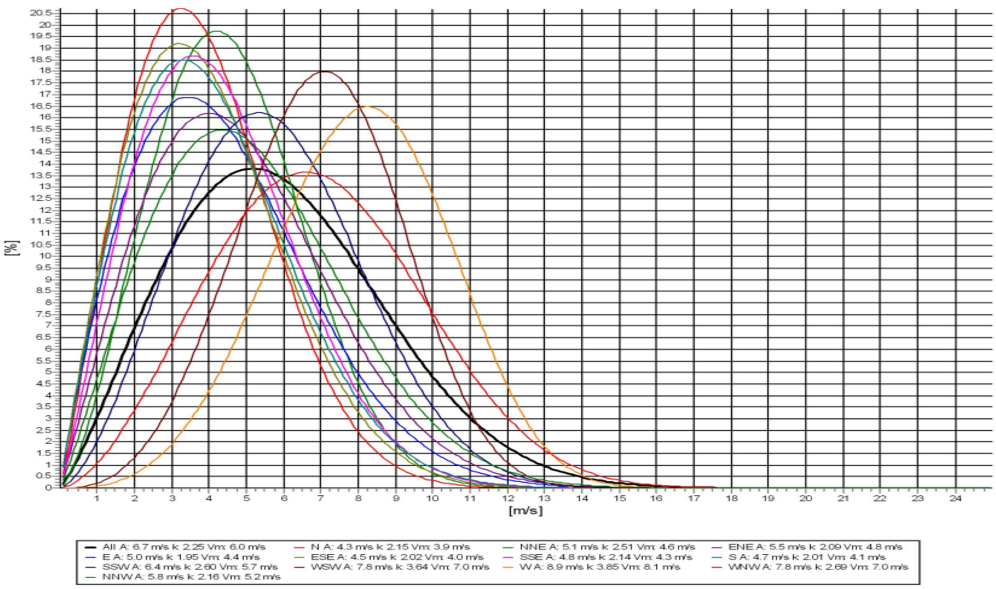

Fig. 3 Sector wise Weibull parameter distribution at 80m height a.g.l.

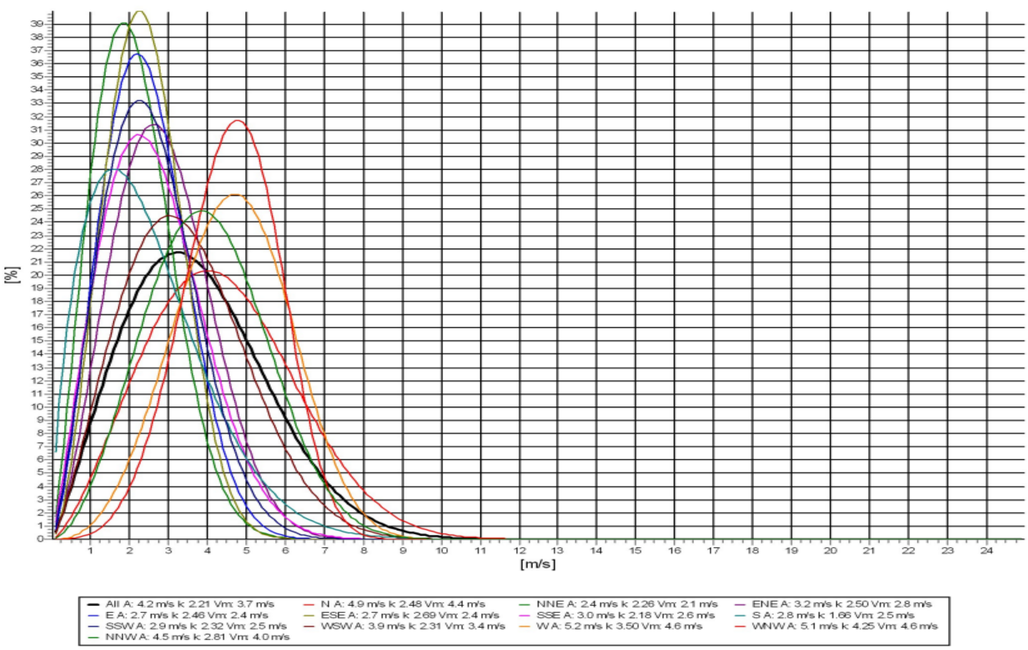

Fig. 4 Sector wise Weibull parameter distribution at 10m height a.g.l.

Fig.3 and Fig. 4 shows the sector wise distribution of Weibull parameter at 80m and 10m height respectively.

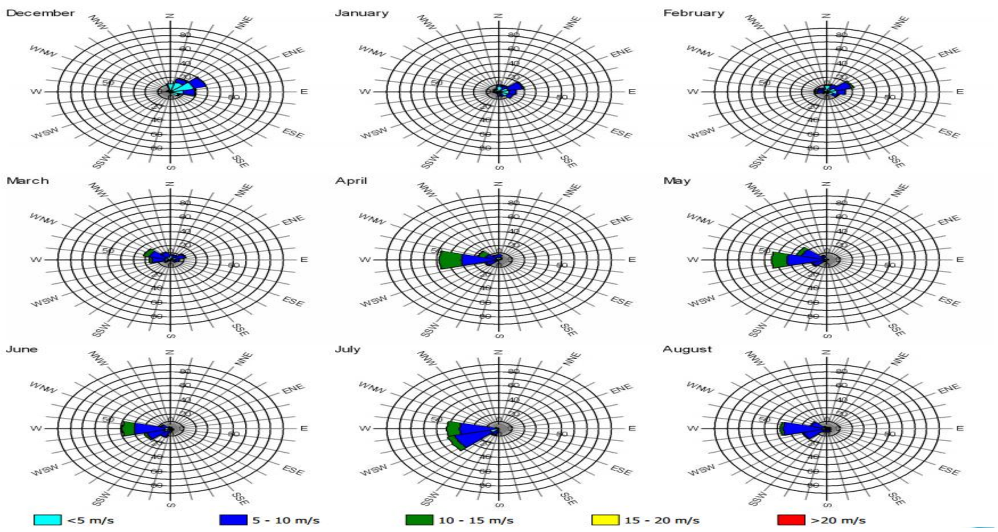

Fig. 5 Energy rose at 80m height

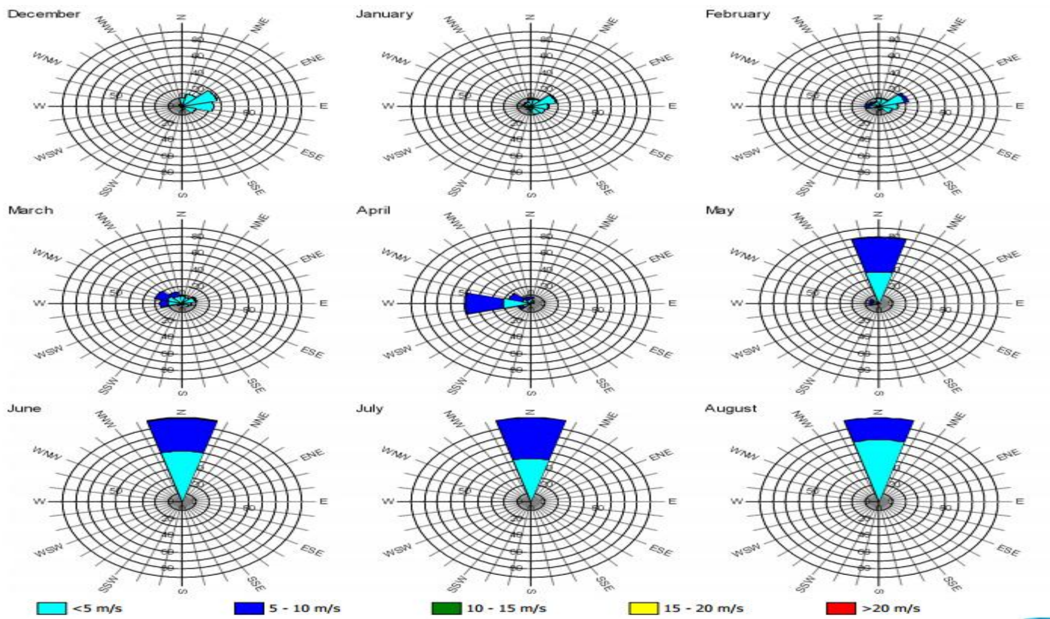

Fig. 6 Energy rose at 10m height

Wind Energ. Sci. Discuss., https://doi.org/10.5194/wes-2018-16
Manuscript under review for journal Wind Energ. Sci.
Discussion started: 3 April 2018

In Fig. 5 (April month) upto 20m/s wind speed has been shown, which produces maximum power density at 80m height. While Fig. 6 indicates that the maximum wind speed can be utilized for the power production is 3 -5 m/s at 10m height. The measured wind speed at 10m a.g.l. can be taken as reference purpose. Further Wind speed has been extrapolated using PL from 50m to 100m and 80m to 100m by $\alpha_{10\text{-}50}$ = 0.2483 and $\alpha_{50\text{-}80}$ =0.1474 respectively. By taking the surface length of z_o 0.3183m, von karman factor 0.4 and friction velocity u_* 0.4316 m/s the wind speed can be found using LogL at 100m a.g.l as 6.20m/s.

The Monin- Obukhuv Length similarity had been applied at Jamogadrani hills which predict that the atmosphere is strongly stable and wind speed using D&H model found to be 6.68m/s. The Richardson Number is 0.35614 which has been used to calculate Monin- Obukhuv scale.

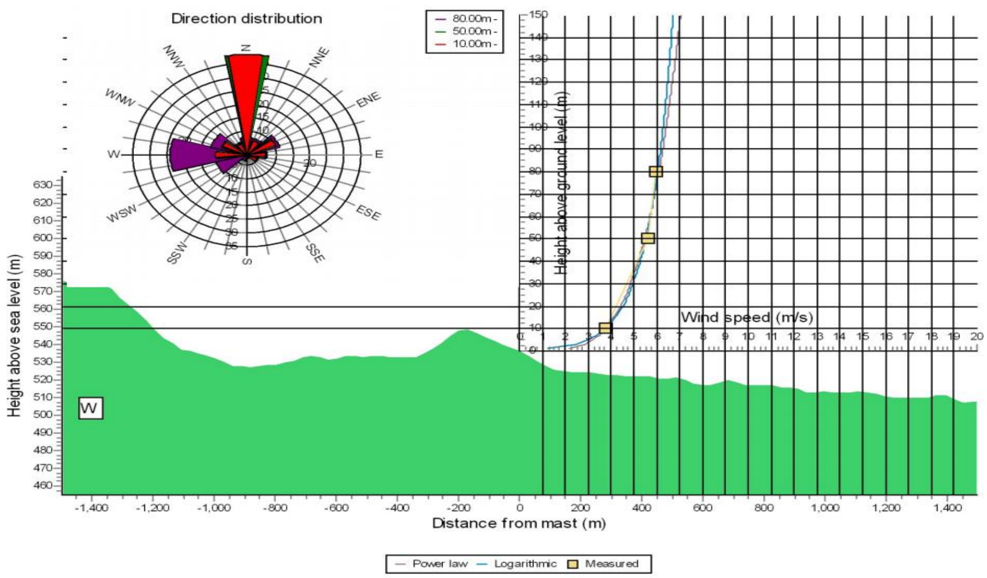

Fig. 7 Mean wind profile using power law and LogL respectively

Table 5 Comparative analysis between different models

Parameter/Results	Predicted by PL ($\alpha_{10\text{-}50}$ = 0.2483)	Predicted by PL ($\alpha_{50\text{-}80}$ =0.1474)	LogL	D&H model
Wind speed in m/s	6.580	6.135	6.204	6.681
RMSE	0.26398	0.18085	0.111701	0.36485
NRMSE	0.04094	0.02905	0.017842	0.056139

It is clear from Table 5 that Log law fitted and best matches the wind profile. RMSE and NRMSE found to be least in case of Log low in compare to PL and D&H model. The actual measured wind speed by wind anemometer is 6.32 m/s at 100m a.g.l. It can be seen from Fig. 7 that the accuracy of the LogL increases from the height above 80m a.g.l.

Wind Energ. Sci. Discuss., https://doi.org/10.5194/wes-2018-16
Manuscript under review for journal Wind Energ. Sci.
Discussion started: 3 April 2018

5. Conclusion

To validate its reliability as a wind speed prediction extrapolations tool for addressing MW WTs, the PL, LogL and D&H model was assessed at hub heights at 10m, 50m, 80m and 100m. Based on a one year data (2016-2017) of 10 min. observations including temperature and pressure data from the Met mast of Jamgodrani hills, all models were compared. The application of model has required prior assessment of sites surface parameter such as α for power law, friction velocity and surface length for Log law and Coriolis factor, ABL height for D&H model. Though, D&H model was actually developed for strong wind conditions subjected to neutral conditions, it was forced to applied for all stability regions.

The PL, LogL and Deaves and Harris model is outperformed upto height 80m a.g.l. within the extrapolating range. The results seem to the LogL capability of best producing at higher level. Since, this model has been found to be suitable for strong adiabatic conditions. However, the overall accuracy of LogL model during these conditions should be chosen as a model's key factor. Practically, in Indian conditions the DH model could not fit appropriate due to two limitations: i) reliable friction observation ii) accurate site's surface length assessment. Since, the value of Z_o has the major effect on DH model.

Based on 10 min. wind speed, pressure and temperature data the minimum RMSE and NRMSE found to be 0.11 and 0.01respctively. The PL exhibited the more accuracy across all extrapolations ranges and for all stability criteria, which is used particularly in predicting wind speed profile variation. Currently, obtained results strongly encourage further uses of the PL, which would be deemed as a future research topic from a wind energy scenario. At Jamgodrani hills LogL proved to be the finest in prediction the extrapolated wind speed, thus supporting its validity over the entire ABL.

References

Barker, E. H., Baxter, T. L., 1975. A note on the computation of atmospheric surface layer fluxes for use in numerical modeling. J. Appl. Met. 14, 620-622.

Binkowski, F. S. 1975. On the empirical relationship between the Richardson number and the Monin-Obukhov stability parameter. Atmospheric Environmental, 9, 453-454.

Businger, J. A., Wyngaard J. C, Izumi Y. and Bradley E. F. 1971. Flux- profile relationships in the atmospheric surface layer. J. Atoms. Sci. 288, 181-189.

Cook, Nicholas J., 1997. The Deaves and Harris ABL model applied to heterogeneous terrain. Journal of Wind Engineering and Industrial Aerodynamics. 66 (1991) 197-214.

Counihan, J., 1975. Adiabatic atmospheric boundary layers: a review and analysis of data from the period 1880−1972. Atmos. Environ. 9, 871−905. http://dx.doi.org/10.1016/0004-6981(75)90088-8.

Davenport,A.,1960.Rationale for determining design wind velocities. Journal of Structural Engineering, ASCE 86,39–68.

Deaves,D.,1981.Computations of wind flow over changes in surface roughness. Journal of Wind Engineering and Industrial Aerodynamics 7, 65–94.

Deaves,D.,Harris,R.,1978.A Mathematical model of the structure of strong winds. Report76. Construction Industry Research and Information Association.

Drew, Daniel R., Barlow, Janet F., Lane, Siân E., 2013. Observations of wind speed profiles over Greater London, UK, using a Doppler lidar. J. Wind Eng. Ind. Aerodyn. 121(2013)98–105.

Dyer, A., 1974. A review of flux-profile relationships. Boundary-Layer Met. 7, 363-312.

Elliott, W.,1958. The growth of the atmospheric internal boundary layer. American GeophysicalUnion39,1048–1054.

Gualtieri, Giovanni., Secci, Sauro ., 2011. Comparing methods to calculate atmospheric stability-dependent wind speed profiles: A case study on coastal location. Renewable Energy 36 (2011) 2189-2204

Gualtieri, Giovanni., 2017. Wind resource extrapolating tools for modern multi-MW wind turbines: Comparison of the Deaves and Harris model vs. the power law. Journal of Wind Engineering & Industrial Aerodynamics 170 (2017) 107–117.

Gualtieri, Giovanni., 2016. Atmospheric stability varying wind shear coefficients to improve wind resource extrapolation: A temporal analysis. Renewable Energy 87 (2016) 376-390.

Kikumoto, Hideki., Ooka, Ryozo., Sugawara, Hirofumi., Lim, Jongyeon., 2017. Observational study of power-law approximation of wind profiles within an urban boundary layer for various wind conditions. Journal of Wind Engineering & Industrial Aerodynamics 164 (2017) 13–21.

Panofsky, H., Dutton, J., 1984. Atmospheric Turbulence: Models and Methods for Engineering Applications. Wiley.

Simiu, E.,Scanlan,R.,1996.Wind effects on structures fundamentals and applications to design. John Wiley and Sons Inc.

Sharma, Pramod Kumar., Baredar, Prashant V. 2017. Analysis on piezoelectric energy harvesting small scale device – a review . https://doi.org/10.1016/j.jksus.2017.11.002.

Sharma, Pramod Kumar., Warudkar, Vilas., Ahmed, Siraj. 2014. Experimental investigation of Al 6061/ Al2O3 Composite and Analysis of its mechanical properties on onshore wind tower using hybrid technique for Indian Condition. Procedia Materials Science 5 (2014) 147 – 153.

Sharma et.al., 2014. A Review on Electromagnetic Forming Process.” Procedia Materials Science 6 (2014) 520 – 527.

Sharma, Pramod Kumar., Warudkar, Vilas., Ahmed, Siraj. 2014. Design and Optimization of 150 m Higher Wind Monitoring Tower (Indian Condition). International Journal of Scientific Engineering and Technology. (ISSN : 2277-1581). 2014 Volume No.3 Issue No.2, pp : 85 – 89.

Tieleman, Henry W., 2008. Strong wind observations in the atmospheric surface layer. Journal of Wind Engineering and Industrial Aerodynamics 96 (2008) 41–77.