Effect of atmospheric stability on the wind resource extrapolating models for large capacity wind turbines: A comparative analysis of power law, log law, 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 provides the better representation of wind profile over homogeneous 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. Nowadays wind resource assessment has been widely dependent on terrain and becomes a key issue for the researchers. It has been found experimentally from earlier work that model of Deaves and Harris shows a better representation of wind profiles on flat terrain at higher heights in comparison to other models such as the PL (power law), the LogL (log law) and the LogLL (Log linear law). This study presents a comparative analysis of three different wind extrapolation models. Based on two year measured wind data from the met mast the at 10 m, 50 m, 80 m, 100 m and 102 m heights, results were compared in different stability classes using Monin-Obukhov similarity theory. The RMSE (root mean square error) and NRMSE (normalized root mean square error were found to be least in case of log-linear model which is 0.11 and 0.01784 respectively in comparison to the PL and Deaves and Harris models.

Keywords: Atmospheric boundary layer, 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 [J/kg.k]
H	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 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
NRMSE	normalized root mean square error

1. Introduction

Accurate measurement of wind resource is necessary to project a wind farm. The earlier method uses cup anemometer and wind vane to measure the wind velocity and direction. Due to the 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 the power law, the logarithmic law and Deaves and Harris model regarding mean wind speed and turbulence intensity. At 10 m height, nonneutral thermal stability affects the wind velocity profile and should not be neglected. Daniel R. Drew et al. 2013 observed that Deaves and Harris wind speed extrapolating model was found to be the best fit at nonequilibrium conditions in urban areas. Hideki Kikumoto et al. 2017 investigated the accuracy of wind speed measurement using the PL in low-speed region. The results were compared and analyzed with Doppler 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 D&H. 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 10 m and 50 m height above ground level 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 the power law and found to be the finest and accurate approach regarding wind speed profile and energy yield calculation in neutral conditions. Some equilibrium wind speed model name as the PL, the 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 the inner boundary layer with a step change in surface roughness for the wind profile predictions. Deaves 1981 utilized the concept for heterogeneous terrain in wind speed extrapolating methods.

Giovanni Gualtieri 2017 tested and compared the DH model with the PL with all stability conditions. The DH model found to be best fitted and tuned, and its accuracy has increased with height from 80 m to 140 m above ground level. Due to increasing demand for energy, wind resource prediction has become a crucial issue markedly for energy investors to accurately analyze the wind speed at a different hub height of wind turbine. It is essential during the feasibility study to abate the cost of wind farm installation. Many researchers worked on different wind extrapolating models such as the PL, the LogL, the LogLL, and DH. Every model has its significance and assumptions depending on the type of terrain where wind speed has predicted. Sharma et. al. 2014 had optimized 150 m higher wind monitoring tower using ANSYS. Sharma et. al. 2014 extended earlier work with the incorporation of nano and piezoelectric materials in their design.

2. Wind Profile extrapolating models

It was the first time when Davenport 1960 originally proposed the PL to design the wind load, especially in structural engineering. Due to the simplicity of the PL model which can applied to larger height in compare to the logarithmic law subjected to various terrain conditions as per Counihan, 1975. Following models had generally been adopted for the wind profile predictions under certain assumptions:

2.1 Deaves and Harris (D&H) model

This model 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 developed to a different kind of heterogeneous terrain. UK, Australia and New Zealand have adapted this model into its wind design codes. If u_* is the friction velocity, k is the von Karman constant = 0.4), z_o is the roughness length, h is atmospheric boundary layer height then velocity v has been defined as:

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

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

$$h = \frac{u_*}{6\,f} \tag{2}$$

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

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

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

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

As per similarity theory,

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

$$V \rightarrow V_G\ and\ \frac{dV}{dz} \rightarrow 0\ as\ z \rightarrow h \tag{6}$$

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 derived from Eq. (5) and holds over a ground surface:

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

It is clear from Eq. (7) That log law satisfies the lower boundary conditions only not the upper one. Typically, it found that the power law does not fit well at the higher height ranger (typically more than 150 m).

2.3 Power law model

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

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

Here, V_{ref} refers to the wind speed at the height say z_{ref}. The Power law indicates the increment of surface wind speed concerning height z. The PL neither satisfies the upper boundary nor the lower boundary conditions. In comparison to log law model, it fits well with 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 30 m to 300 m a.g.l. The value of α varies concerning 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

Monin defines the turbulence within the surface boundary layer- Obukhov 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- Obukhov length scale L can calculate by computing the Bulk Richardson number which requires only single wind speed and temperature measurements at two heights. Gradient and bulk Richardson number 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 a single height (Barker and Baxter, 1975)

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

$$\varepsilon = \frac{\varphi_m^2}{\varphi_h} R_i \text{ (Businger et.al., 1971) suggested} \tag{12}$$

$\frac{\bar{z}}{L} = \varepsilon$, $\bar{z}$ stands for the geometrical mean height of z_1 and z_2, and φ_m and φ_h are the nondimensional 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

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

$\bar{z} = \frac{z_1+z_2}{2}$, $\bar{z}$ is the mean height (16)

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

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

L depends upon two stability conditions

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

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

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

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

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

Where η_2 η_o λ_1 λ_2 are the function of Monin- Obukhov length L. G is the function of Ri and mean gradient height z. F stands for the logarithmic function of speed and friction velocity.

3. Observation and site details

Jamgodrani hills have a huge potential regarding power production. The 100 m mast 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- Obukhov 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

Fig. 1 Met mast location (The point shows the met mast location, Source Google Earth)

Weibull parameter (k and c) calculated by two different methods namely as MLM and MMLM. It is very much clear from the Table 3 in comparison to Table 2 Weibull parameter are more than Table 2. Experimentally, it found that the Weibull parameters calculated y the MMLM provides more accurate results in comparison to MLM.

MLM is a widely accepted method to estimate the Weibull parameter. It required a more extensive tool for mathematical calculations. In the first step, k 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 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.

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

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

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 calculated at different heights from ground level. It is clear from Table 4 that the annual wind speed increase concerning height, but mean turbulence intensity decreases. Due to more predominate viscous and obstruction effect near the ground level wind turbulence is more. Turbulence intensity seems to decrease with the height due to a decrease in surface shear stress.

Table 4 Wind characteristics

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

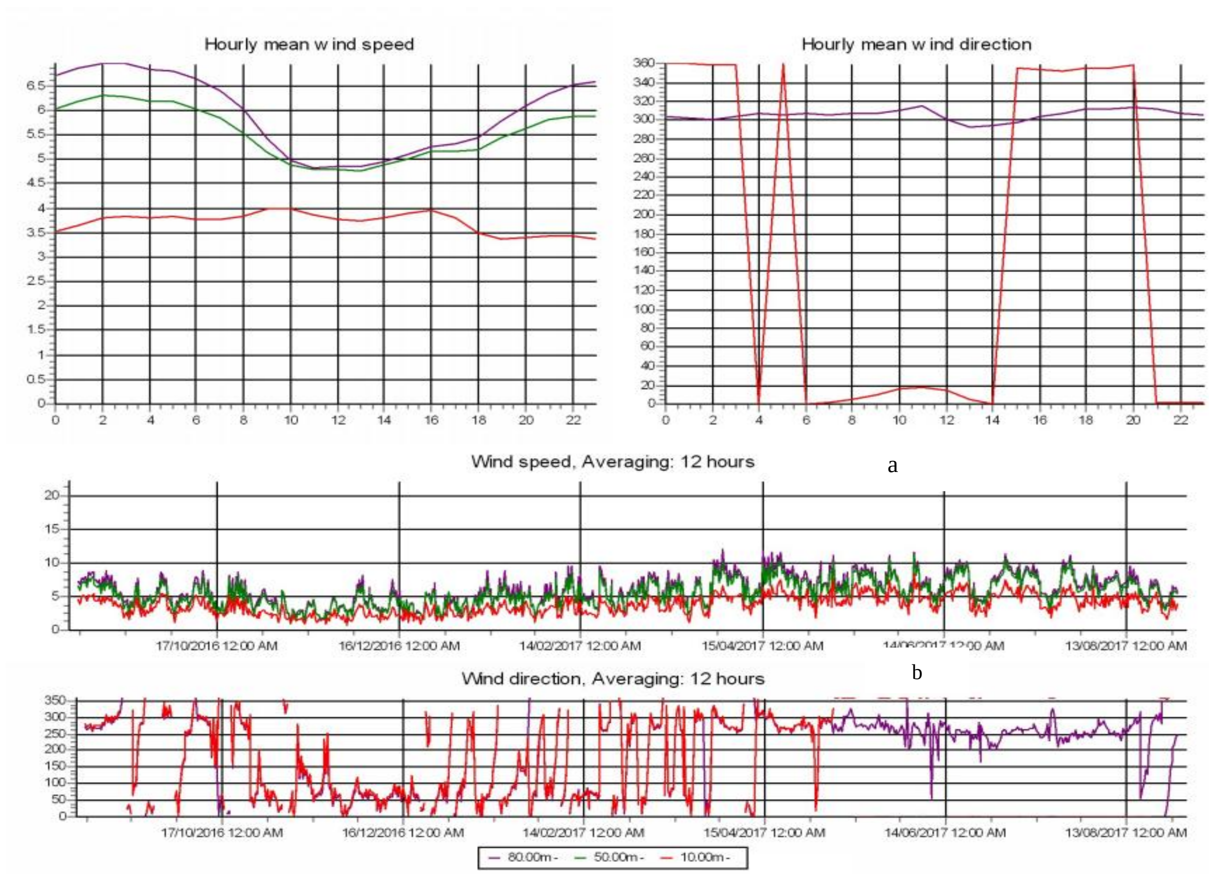

Fig. 2 Wind speed and direction variation (Source: windPRO 3.1) (a): Variation of hourly wind speed in m/s and Direction in degree, (b): average wind direction, (c): wind direction at 50 m, 80 m, and 100 m heights.

The hourly variation of wind speed and direction has been shown in Fig. 2 at 10 m, 50 m, and 80 m height respectively. Blue shown in Fig. 2 signifies the wind speed and direction at 100 m hub heights. Weibull parameters have been divided into 12 sectors with the given direction and typically illustrated in Fig.3 and Fig. 4 respectively at 80 m and 10 m height respectively.

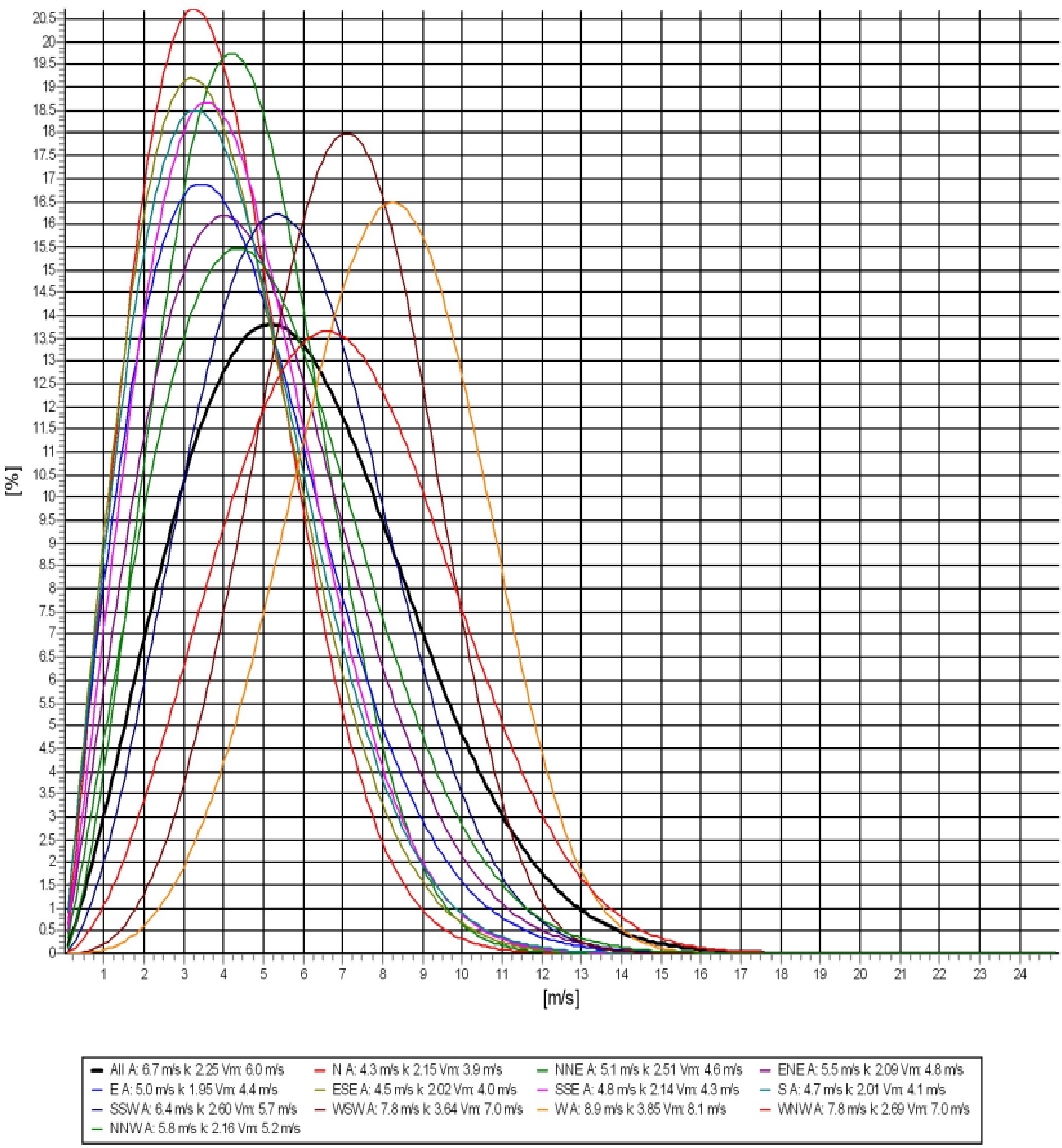

Fig. 3 Sector-wise Weibull parameter distribution at 80m height a.g.l. (Source: windPRO 3.1)

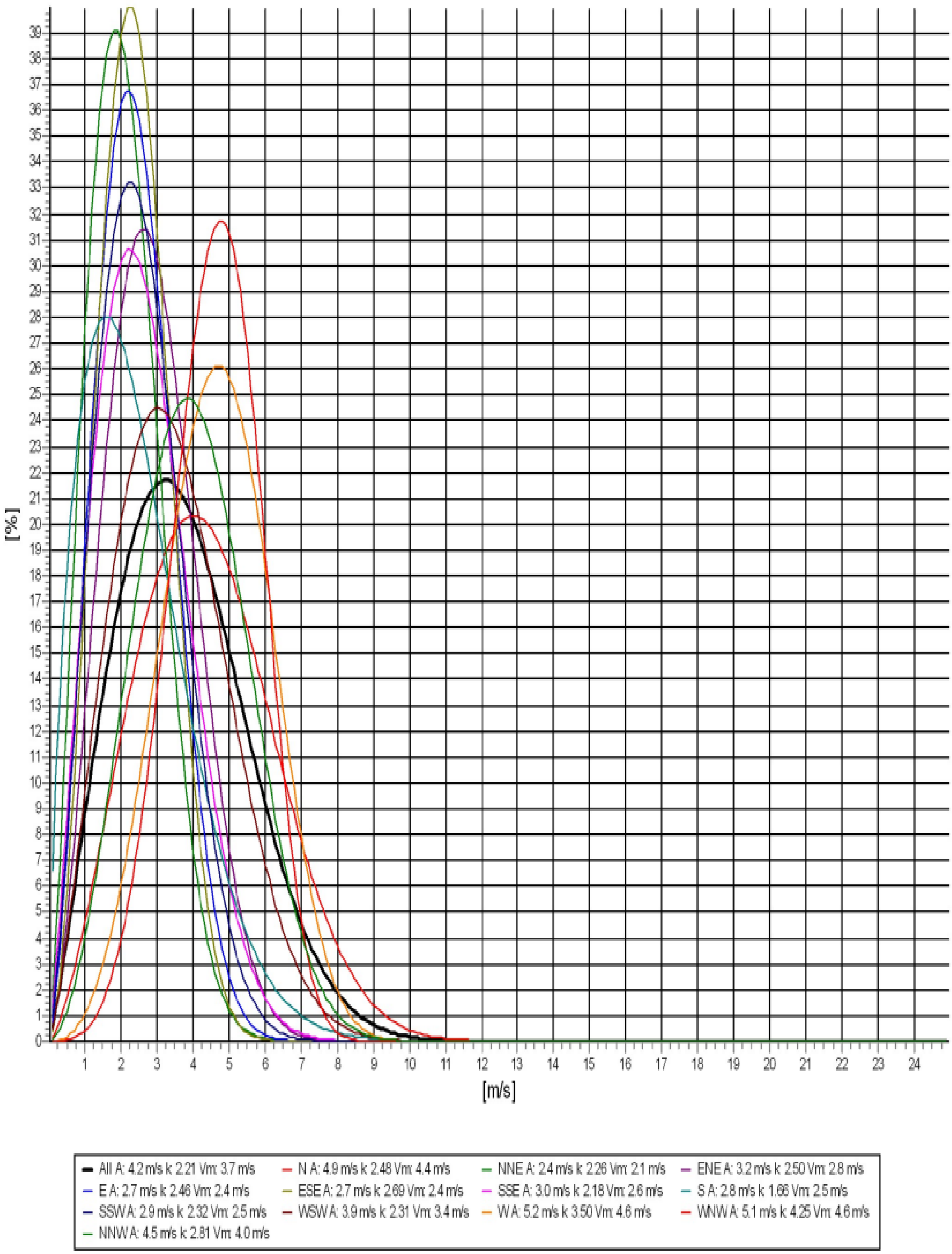

Fig. 4 Sector wise Weibull parameter distribution at 10m height a.g.l. (Source: windPRO 3.1)

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

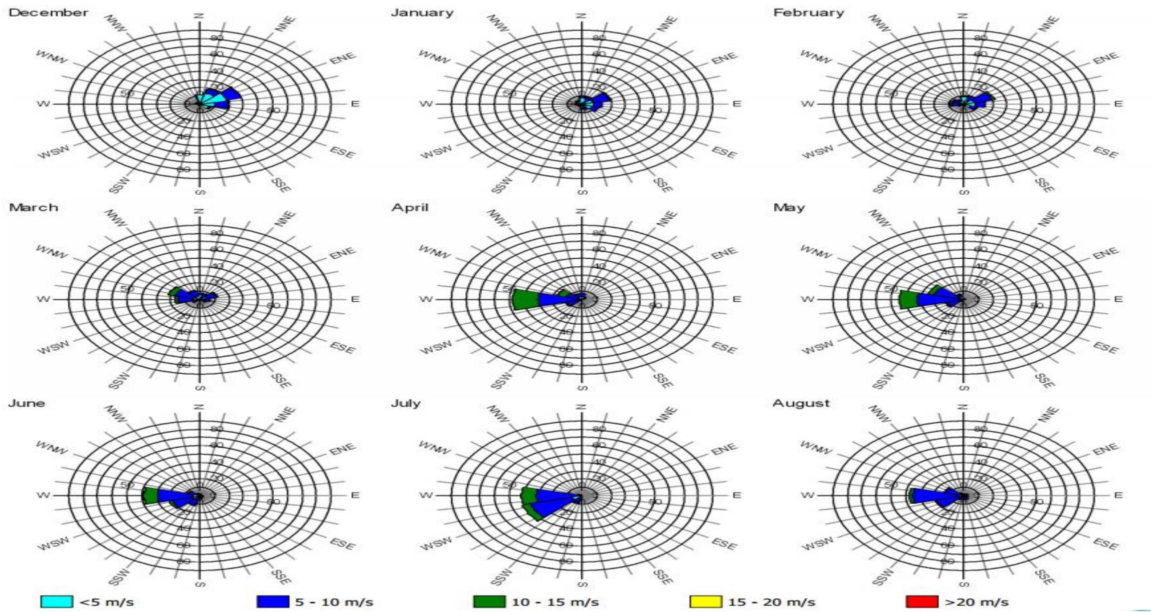

Fig. 5 Energy rose at 80m height (Source: windPRO 3.1)

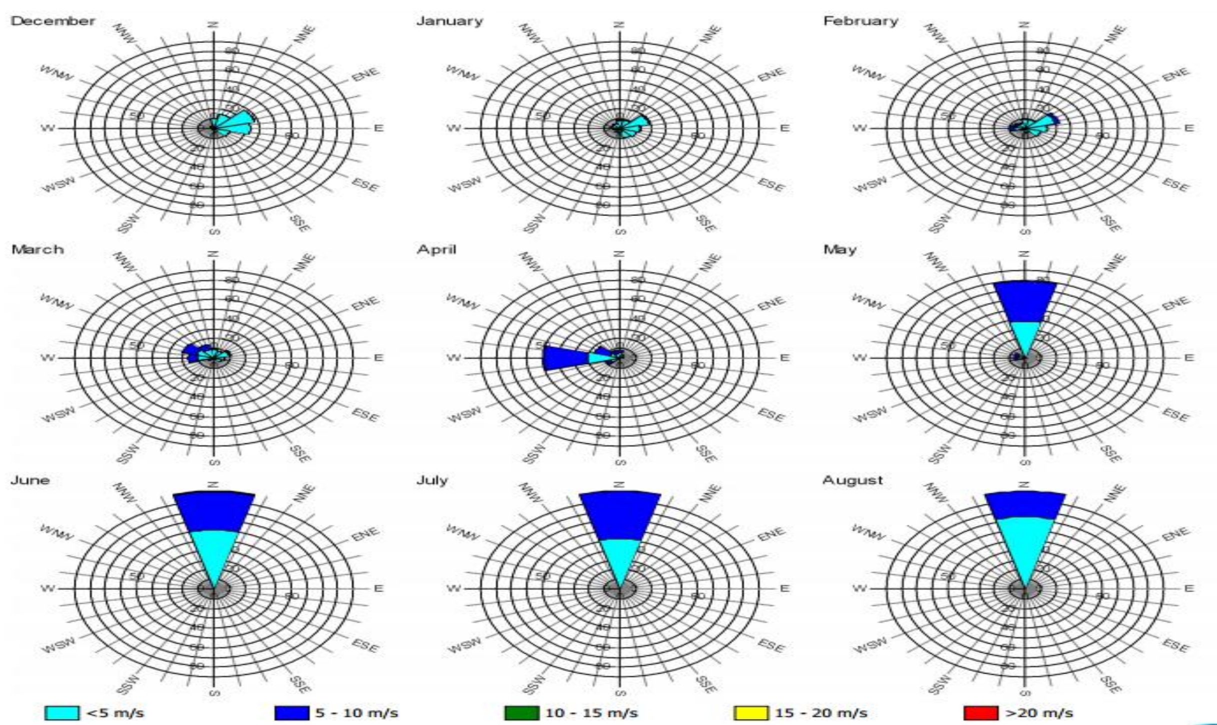

Fig. 6 Energy rose at 10m height (Source: windPRO 3.1)

In Fig. 5 (April month) up to 20m/s wind speed 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 for reference purpose. Further Wind speed has been extrapolated using the 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_0 0.3183m, von Karman factor 0.4 and friction velocity u_* 0.4316 m/s the wind speed can be found using the LogL at 100m a.g.l as 6.20m/s.

The Monin- Obukhov Length similarity had 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- Obukhov scale.

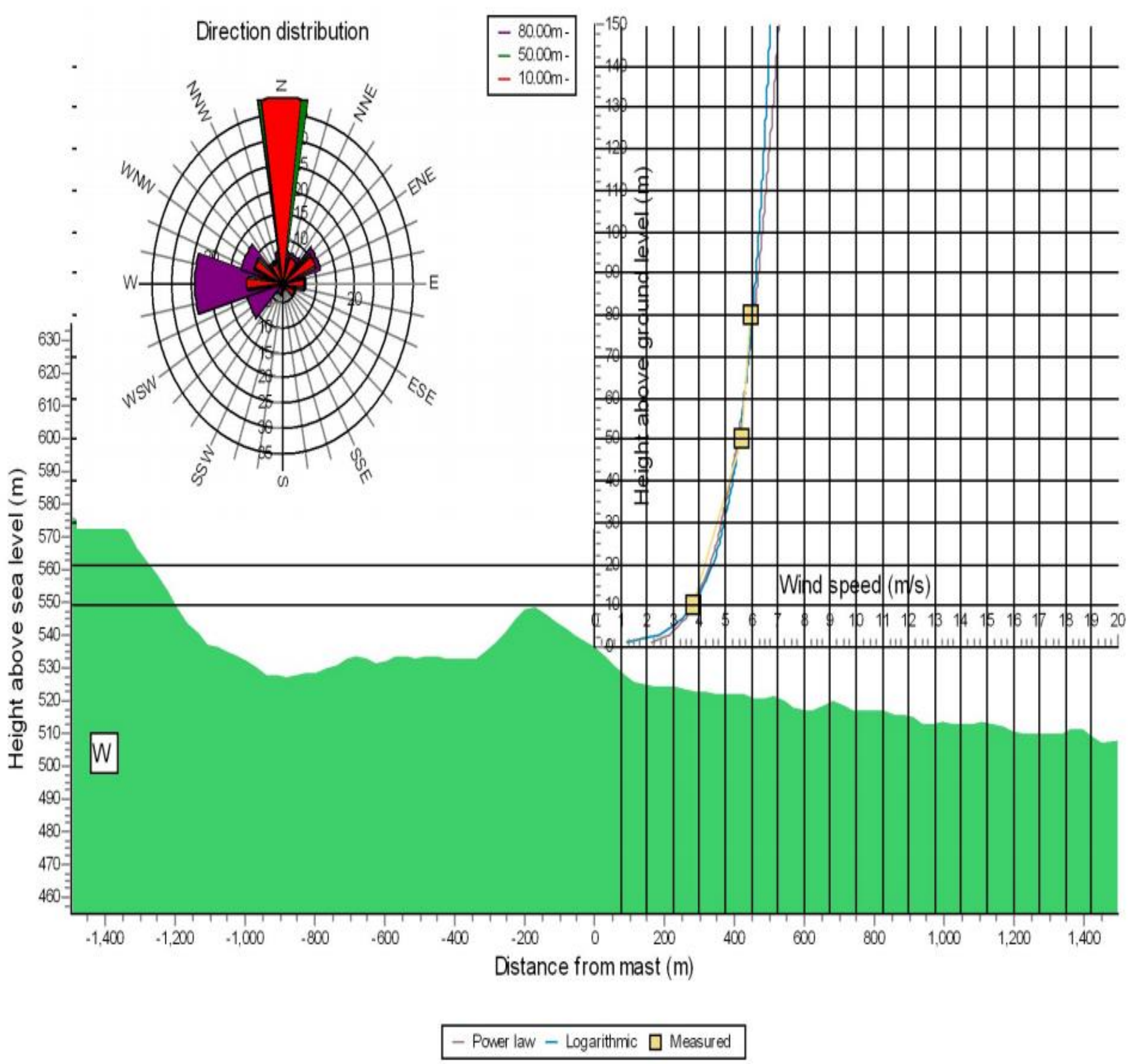

Fig. 7 Mean wind profile using power law and LogL respectively

Table 5 Comparative analysis of 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 see from Fig. Seven that the accuracy of the LogL increases from the height above 80m a.g.l.

5. Conclusion

To validate its reliability for addressing MW WTs, the PL, LogL and D&H model assessed at hub heights at 10 m, 50 m, 80 m and 100 m. Based on a two-year wind data of 10 min. Observations including temperature and pressure data from the met mast of Jamdani hills, all models were compared. The application of models 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 developed for strong wind conditions subjected to neutral conditions; it forced to apply for all stability regions.

The RMSE and NRMSE were found to be at least for the PL, the LogL, Deaves and Harris model up to height 80m a.g.l. Within the extrapolating range. The result seems to the LogL capability of best producing at a higher level. This model was found suitable for strong adiabatic conditions. However, the overall accuracy of LogL model during these conditions should choose 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. 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 deem as a future research topic from a wind energy scenario. At Jamgodrani hills, the LogL proved to be the finest in the prediction of the extrapolated wind speed, thus supporting its validity over the entire ABL.

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