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Techno-Economic Evaluation of Wind Power Generation Through CDFs and LCOE in Shahabad Village (Sindh)

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Abstract: **Wind data of one year has been selected for the village Shahabad, district Thatta, Sindh. Five cumulative distribution functions name as Weibull, Gamma, Lognormal, Generalized Extreme Value and Rayleigh used. Five tests namely Root Mean Square Error (RMSE), Mean Absolute Error (MAE), Mean Square Error (MSE), Coefficient of Correlation (R) and Coefficient of Determination (D) used for the comparison of cumulative functions. Wind speed on yearly seasonal and hourly basis are evaluated. Six wind turbine models are selected for power generation capacity. Among all the distribution functions Weibull performs best and after Weibull at the second Rayleigh performs best. Maximum capacity factor among all turbines is of FWT 120/3000 with payback period of six years.**

***Index Terms*— CDFs, Goodness of Fit Tests, Power Generation, LCOE, Payback period.**

I. INTRODUCTION

Pakistan's energy demand is increasing because of the increase in population and installation of industries under China Pakistan Economic Corridor (CPEC) [1]. It is investing in sustainable energy mainly wind & solar energy because of the Sustainable Development Goals (SDGs) [2] & Goal 7 under Conference of Parties (COP 23) [3]. This led policy makers to enact new laws and initiate program like Alternative Energy Development Program (AEDP) [4]. Thanks to above efforts, there is huge invest in wind energy generation which has caused increase in share of renewable energy into the energy mixture of Pakistan [5]. Before leasing the land for wind energy exploitation, it is important to determine the wind characteristics and forecasting the power production of many wind turbine models [6] evaluation is also essential for the satisfaction of investors [7]. Thus, wind resource estimation, choosing suitable wind turbines and economic evaluation plays an important role [8]. There are many cumulative distribution functions in literature, which are used for the estimation of wind characteristics of a site [9]. Statistical tests like Root Mean Square Error (RMSE), Mean Squared Error(MSE), Mean Absolute Error (MAE), Coefficient of Determination (R) and Coefficient of Correlation (R2) [10]. The wind power, energy, and used to get the capacity factor of a wind turbine by using its power curve [11]. The capacity factor and rated power of a wind turbine determines the power production [12]. An economic approach like cash flow method can also be used to forecast the revenues and loses over the period of a project (say about 25 years) [13]. Therefore, this study will be very much helpful in the forecasting of wind resource estimation and economics of a wind power project for the life expectancy of 25 years. Also, this work will help to invest in clean and green energy. Moreover, this will be a step towards fulfilling Sustainable Development Goals (SDGs) and Goal 7 (affordable and clean energy) of COP 23. To tackle the climate change and mitigating carbon emissions.

II. WIND DATA ASSESSMENT

When consider the wind power assessment, it is necessary to have knowledge of wind characteristics, as wind speed is varying time to time and continuously changes its direction. The magnitude and density of wind speed is different during different seasons.

A. *Average Wind Speed*

Average wind speed is the mean speed over a specific period.

$$v_{avg} = \frac{1}{n}\sum_{i=1}^{n} v_i \quad (1)$$

B. *Variance*

The average wind speed is given by equation:

$$\sigma^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left(v_i - v_{avg}\right)^2 \quad (2)$$

C. *Standard Deviation*

Standard deviation is obtained from given equation:

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(v_i - v_{avg}\right)^2} \quad (3)$$

D. *Air Density*

Air density can be calculated using equation:

$$\rho = \frac{P}{R\times T} \quad (4)$$

E. *Turbulence Intensity*

Ratio of standard deviation of fluctuating wind speed to the mean wind speed.

$$TI = \frac{\sigma}{V} \quad (5)$$

F. Wind Power Density

Wind power density WPD is a measure of wind power found in any area.

$$WPD = \frac{P}{A_T} = \frac{1}{2}\rho c_p v^3 \quad (6)$$

Where ρ is air density, v is wind velocity, A is Area, P is output power.

G. Energy Density:

Energy density is the amount of energy stored in given system.

$$E = T\int\left(\frac{K}{c}\right)\left(\frac{V}{c}\right)^{k-1}\exp\left(-\frac{V}{c}\right)^{k}.P(V)dV \quad (7)$$

H. Shear profile:

$$\alpha = \frac{0.37-0.088\ln(h)}{1-0.088\times\ln\left(\frac{2}{10}\right)} \quad (8)$$

I. Power Law:

Relation between two quantities such that one is proportional to a fixed power of other:

$$v_2 = v_1\left(\frac{z_2}{z_1}\right)^{\alpha} \quad (9)$$

Wind power is proportional to cubic wind speed it is essential to have knowledge of related site characteristics.

J. Capacity Factor:

Capacity factor average is a production unit that is capable of producing higher output compared to real production units over a period of time.

$$C.F = \frac{average\ power\ output}{peak\ power\ output} * 100 \quad (10)$$

K. Power Output:

The output power is

$$P_{out} = P_R C_f \quad (11)$$

Where P_{out} is output power and *Cf* is capacity factor

L. Annual Energy Production

The annual power output of wind turbine is the total amount of energy produced in a full year.

$$AEP = P_{out} * \frac{8760kwh}{year} \quad (12)$$

AEP is annual energy production; P_{out} is output power and 8760 is number of hours in a year.

III. Distribution Functions

A. Rayleigh Distribution

Rayleigh distribution function is two parameters of the cumulative distribution function with the shape parameter (k) and a scale parameter (c). The equation of Rayleigh distribution function is given:

$$f(v,a) = 1 - \text{expexp}\left[-\frac{1}{2}\left(\frac{v}{a}\right)^2\right] \quad (13)$$

$$c = \frac{m}{\Gamma(1+\frac{1}{k})} \quad (14)$$

B. Gamma Distribution:

The gamma distribution function is two parameter distribution function.

$$G(v) = \int \quad \frac{v^{a-1}}{b^a\Gamma(a)}\exp\left(-\frac{v}{b}\right)dv \quad (15)$$

The equations of parameters are given below:

$$\alpha = \frac{m^2}{s^2} \quad (16)$$

$$\beta = \frac{s^2}{m} \quad (17)$$

C. Lognormal Distribution:

Lognormal distribution function is used for analyzing the data it is has two parameters called location parameter (μ) and shape parameter (σ) erf is gaussian error function.

$$f(v,\mu,\sigma) = \frac{1}{2} + \frac{1}{2}\text{erf}\left[\frac{\ln(v)-\mu}{\sigma\sqrt{2}}\right] \quad (18)$$

$$\text{erf}(v) = \frac{2}{\sqrt{\pi}}\int_0^v \quad \exp(-t^2)dt \quad (19)$$

The parameters are obtained from given equations (20-21)

$$\alpha = ln\left[\frac{m}{\sqrt{1+\frac{s^2}{m^2}}}\right] \quad (20)$$

$$\beta = \sqrt{\ln\left(1+\frac{s^2}{m^2}\right)} \quad (21)$$

D. Generalized Extreme Value Distribution:

$$\exp\left\{-\left[1-\frac{k}{\alpha}(v-\mu)\right]^{\frac{1}{k}}\right\} \text{if } k \neq 0 \quad (22)$$

E. Weibull Distribution:

The Weibull distribution function is a continuous distribution function. Weibull distribution function is measured with the help of parameters. It is two parameters function named as shape parameter and scale parameter (k and c).

$$f(v,k,c) = 1 - exp\left[-\left(\frac{v}{c}\right)^k\right] \quad (23)$$

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

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

IV. Validation of Distribution Functions

Wind speed performance can be achieved by using different goodness of fit tests through these tests we can know which one is best fit on data from different CDFs. For this purpose, here are five tests namely coefficient of correlation, coefficient of determination, mean absolute error, mean square error, root mean square error.

A. The coefficient of correlation:

$$R = \frac{N(\sum_{i=1}^{N} Z_i V_i) - (\sum_{i=1}^{N} Z_i)(\sum_{i=1}^{N} V_i)}{\sqrt{N(\sum_{i=1}^{N} Z_i^2) - (\sum_{i=1}^{N} Z_i)^2}\sqrt{N(\sum_{i=1}^{N} V_i^2) - (\sum_{i=1}^{N} V_i)^2}} \quad (26)$$

B. The coefficient of Determination:

A coefficient of determination is a measure used to define how much variability a single factor can be caused by its relationship to something related.

$$R^2 = \frac{\sum_{i=1}^{N}(V_i-\bar{V})^2 - \sum_{i=1}^{N}(Z_i-\bar{V})^2}{\sum_{i=1}^{N}(V_i-\bar{V})^2} \quad (27)$$

C. Mean Absolute Error:

$$MAE = \frac{1}{N}\sum_{i=1}^{N}(|Z_i - V_i|) \quad (28)$$

D. Mean Square Error:

A mean square error measures the square root of an error, i.e. a square measure of the difference between the approximate value and the actual value.

$$\mathrm{MSE} = \frac{1}{\mathrm{N}}\sum_{\mathrm{i}=1}^{\mathrm{N}}(\mathrm{Z_i} - \mathrm{V_i})^2 \quad (29)$$

N is number of data points.

E. Root Mean Square Error:

RMSE is a standard deviation of residual (predictive errors). Specify how much data is focused on the best equation line. RMSE is a good measure of accuracy, but only comparing the errors of guessing different models or modeling of a particular variable and not between variables, as it depends on the scale.

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(V_i - Z_i)^2\right]^{1/2} \quad (30)$$

V. Economics Of Wind Power Plant

A. Levelized Cost of Energy:

LCOE is an economic measure used to compare the total cost of generating electricity for all different power generation technologies.

$$\mathrm{LCOE} = \frac{\mathrm{CAP_{Cost}.FCR + C_{om}}}{\mathrm{AEP}}(\mathrm{cost/kWh}) \quad (31)$$

B. Fixed Charge Rate (FCR) and Present Worth (P):

$$\mathrm{FCR} = \frac{\mathrm{d(1+d)^t}}{\mathrm{(1+d)^t-1}}\mathrm{x}\frac{1-(\mathrm{T.PV_{dep}})}{(1-\mathrm{T})} \quad (32)$$

$$P = F_c\frac{1}{(1+d)^n} \quad (33)$$

P present worth, *F* future worth, *d* discount rate, *n* number of compounding periods or the expected life of an asset.

C. The Net Present Value:

Net present value is the difference between the current cash flow value and the current cash flow over a period.

$$NPV_T = [NPV(B_A) + NPV(S)] - [C_i + NPV(C_{om})] \quad (34)$$

D. The Annual Benefits:

$$B_A = C_{kWh}AEP \quad (35)$$

E. The Operation and Maintenance:

Cost related to operating and maintaining the component

$$\mathrm{C_{om}} = \mathrm{aC_i} \quad (36)$$

F. Annual Depreciation:

Annual depreciation is the average annual rate at which depreciation is charged on a fixed asset.

$$\mathrm{D_A} = \frac{\mathrm{C_i - S}}{\mathrm{n}} \quad (37)$$

G. System Payback Period:

The payback period is the number of months or years that must be taken to repay the initial investment.

$$SPB = \frac{C_i}{(AEP.P_S - C_{om})} \quad (38)$$

H. Return On Investment:

Return on investment or return on cost is is the ratio between income and investment.

$$\mathrm{ROI} = \frac{\mathrm{PVB-PVC}}{\mathrm{PVC}} \quad (39)$$

VI. Results And Discussion

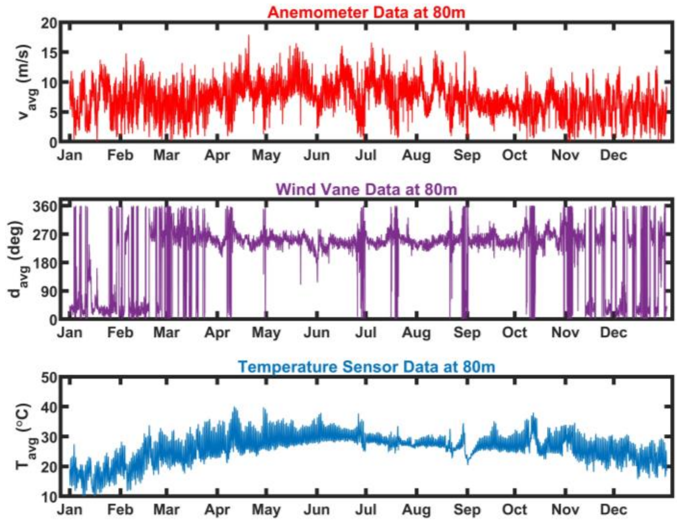

Fig.1. Shows the sensors data

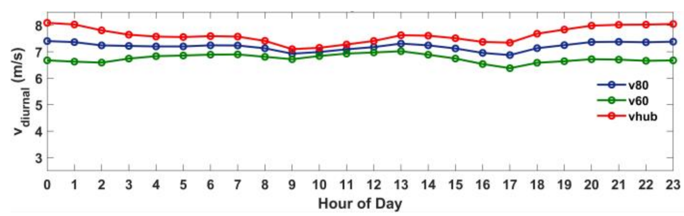

Fig.2. Represent diurnal wind speed at the height of 100, 80m and 60m

The availability of wind speed can be used to wind potential in hourly basis. The recorded data of site (Shahabad village) at the height of 100m, 80m and 60m.it is observed that for 100m, 80m and 60m the maximum wind remained 8m/s, 7.4m/s and 6.8m/s from 9pm to 11pm.

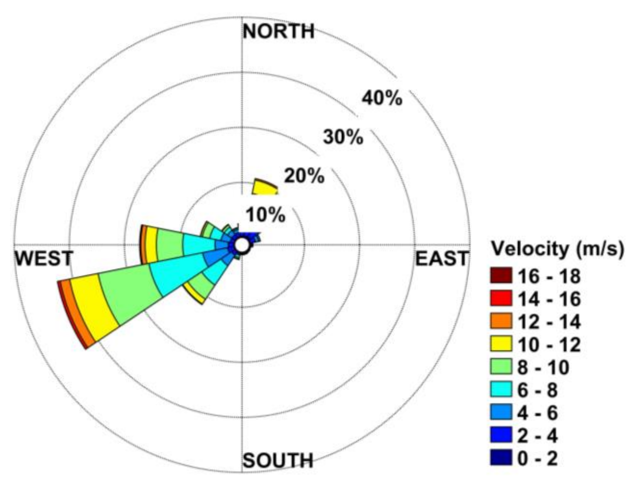

Fig.3. Shows the wind rose diagram for the hub height

Figure 4 shows the CDFs graphs of seasonal and yearly wind speed at 100m. The five cumulative distribution functions are Weibull distribution function, gamma distribution function, Lognormal distribution function, Generalized extreme value function and Rayleigh distribution function. For understanding which function is best fit over data here used five goodness of fit tests mean square error, root mean square error mean absolute error, coefficient of correlation and coefficient of determination.

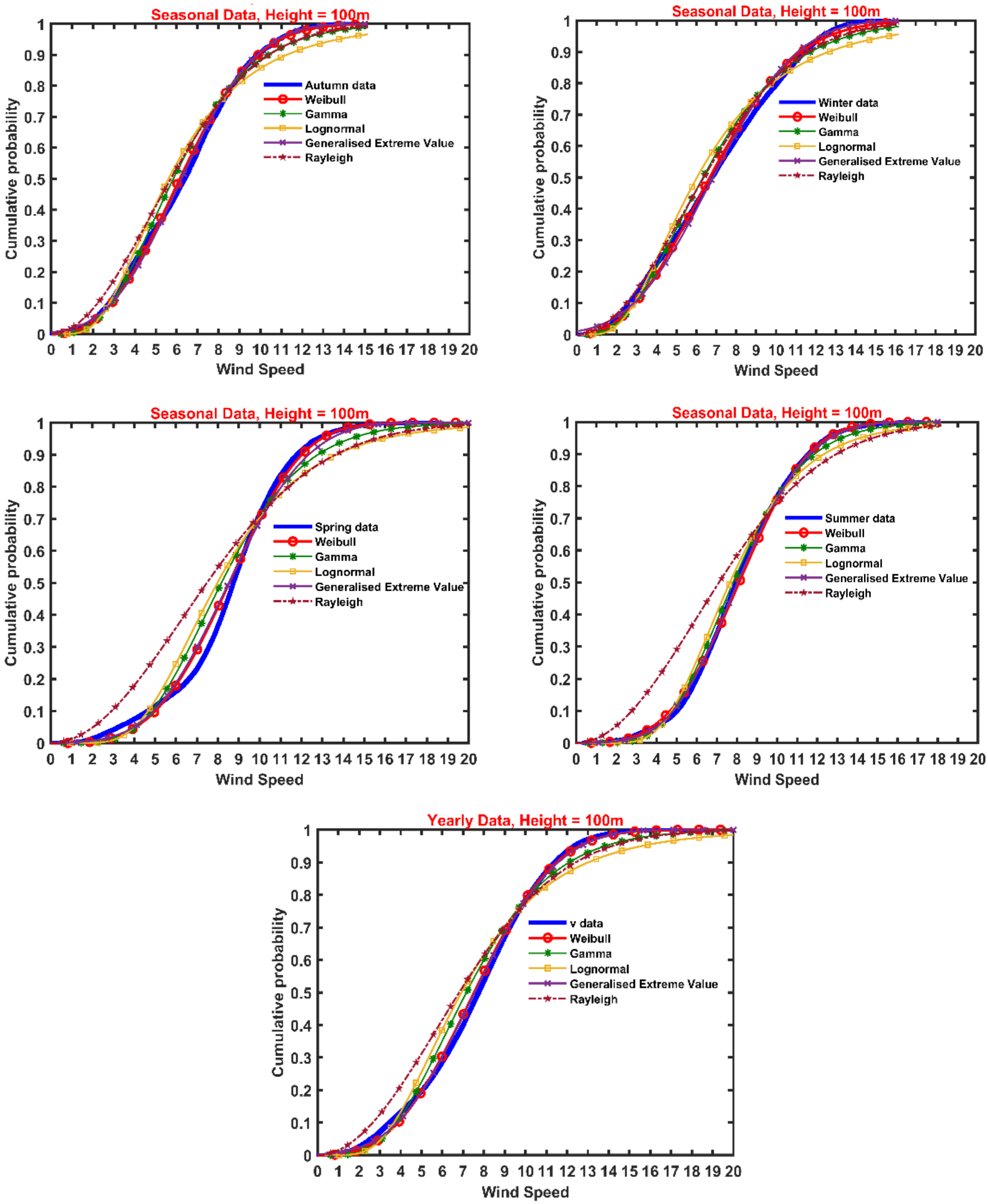

Fig.4. Shows various CDFs over the seasonal and yearly wind speed data at the hub height of a wind turbine

TABLE I: GIVES DETAIL OF GOODNESS OF FIT TEST OF LOCATION (SHAHABAD VILLAGE) AT 100M HEIGHT

	Methods	MSE	RMSE	MAE	R	D
Yearly	Weibull	**0.0000804**	**0.0089639**	**0.006504**	**0.982107**	**0.964533**
	GEV	0.0000751	0.0086638	0.006384	0.982909	0.96611
	Gamma	0.000362	0.0190254	0.014156	0.915927	0.838923
	Rayleigh	0.0005057	0.0224875	0.017862	0.883362	0.780328
	Log Normal	0.0006794	0.0260655	0.020156	0.838934	0.70381
Autumn	**Methods**	**MSE**	**RMSE**	**MAE**	**R**	**D**
	GEV	0.003662	0.060516	0.041522	**0.976109**	**0.952789**
	Rayleigh	**0.00314**	**0.056031**	0.041499	0.948102	0.898897
	Gamma	0.003609	0.060071	0.04164	0.944245	0.891599
	Log Normal	0.003527	0.059389	**0.04113**	0.893855	0.798978
	Weibull	0.016925	0.130097	0.053001	0.015269	0.000233
Winter	**Methods**	**MSE**	**RMSE**	**MAE**	**R**	**D**
	Weibull	0.002569	0.050684	0.037628	**0.96912**	**0.939193**
	Rayleigh	**0.002334**	**0.048312**	0.037472	0.968116	0.937249
	GEV	0.00257	0.050698	0.037355	0.958826	0.919348
	Gamma	0.002587	0.050862	0.037445	0.940449	0.884443
	Log Normal	0.002642	0.051397	**0.036628**	0.888173	0.788851
Spring	**Methods**	**MSE**	**RMSE**	**MAE**	**R**	**D**
	Weibull	0.002865	0.053521	0.037418	**0.952428**	**0.90712**
	GEV	0.002682	0.051791	0.037403	0.93776	0.879394
	Gamma	0.00266	0.051574	0.037558	0.860663	0.74074
	Log Normal	0.002544	0.050441	0.037062	0.776079	0.602299
	Rayleigh	**0.001945**	**0.044097**	**0.036865**	0.719656	5.18E-01
Summer	**Methods**	**MSE**	**RMSE**	**MAE**	**R**	**D**
	GEV	0.002345	0.048421	0.033296	**0.994575**	**0.98918**
	Weibull	0.002303	0.047987	0.033301	0.988451	0.977035
	Gamma	0.002331	0.048283	0.033474	0.98292	0.966131
	Log Normal	0.00228	0.047749	0.033389	0.955087	0.91219
	Rayleigh	**0.001583**	**0.039787**	**0.032917**	0.821951	0.675604

TABLE II: PROVIDES POWER CHARACTERISTICS OF WIND TURBINES

WT	kW	MWh	C.F
WT_1	1691.66	14818.97	56.39%
WT_2	1332.43	11672.11	53.30%
WT_3	1338.06	11721.39	48.13%
WT_4	1214.09	10635.43	48.56%
WT_5	868.37	7606.94	34.73%
WT_6	1011.54	8861.11	33.49%

TABLE III: PROVIDES ECONOMIC CHARACTERISTICS OF WIND TURBINES

WT	LCOE	SPB	ROI	NPV
WT_1	0.041	6	31%	7992247
WT_2	0.043	7	28%	5924596
WT_3	0.048	7	24%	5463651
WT_4	0048	7	24%	3092734
WT_5	0.067	10	15%	2071333
WT_6	0.069	10	14%	2318244

VII. CONCLUSION

Pakistan has a great source of wind energy. In this paper, the data of the Shahabad village air service is analyzed by the authors. For technical purposes the five distribution functions used are Weibull, Gamma, Lognormal, Generalized Extreme Value and Rayleigh. Five advantages of competency testing are used to evaluate the selection of the best distribution function. Wind speed measurements are made per hour, year, and season.

From statistical performance it is clearly understood that in yearly Weibull is best perform from other functions and in seasonal data both Weibull and Rayleigh are best performed at 100m heights. In this study six wind turbine models are used and their capacity factor and rate of return among all the turbines the highest capacity factor and rate of return of FWT 120/3000 and lowest payback period is of FWT 120/3000.

ABBREVIATIONS

AEP = Annual Energy Production,
CF = Capacity Factor,
C_{om} = Cost of Operation and Maintenance,
ERF = Error Function,
LCOE = Levelized Cost of Energy,
MSE = Mean Square Error,
MAE = Mean Absolute Error,
NPV = Net Present Value,
P_{out} = Output Power,
RMSE = Root Mean Square Error,
ROI = Rate of Return on Investment,
SPB = System Payback Period,
WPD = Wind Power Density,
WT = Wind Turbine Model,
WT_1 = FWT 120/3000,
WT_2 = Leitwind LTW101 2500,
WT_3 = GE General Electric GE 2.75-103,
WT_4 = WDRVM WD2.5-103,
WT_5 = Nordex N80 Alpha,
WT_6 = Enercon E-82 E4 3.000,

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