1. Introduction

India is a rapidly growing country in the world and its demand for energy requirement also increases remarkably with its economic growth. However, with its limited supply of fossil fuel, India is looking forward beyond the conventional sources of energy. The conventional sources of power generation in the country are thermal power plants which use coal as its primary fuel. However, with the advancement of technology, India is switching towards alternate sources of energy that are clean, cheaply available in abundance and are having the capability to replace the conventional sources of power generation. According to the release by the European Commission and Netherlands Environmental Assessment Agency released in 2015 **[1]**, India ranks 4th among the CO_2 emission countries with a contribution of 6.81*%* of the total amount of CO_2 emission. As part of the Global Climate Treaty (held at Kyoto, 1997), and the Paris agreement within the United Nations Framework Convention on Climate Change (UNFCCC), the country has an aim to combat global warming. On this direction, it is continuously progressing to cut down carbon emission and to achieve the target and hence it is rapidly switching towards renewable sources of energy, namely solar energy, wind energy, bio-fuel energy, etc. to meet its energy demand. Particularly on wind energy sector, India has shown the remarkable development, and now it is the fourth largest producer of the wind energy with an installed capacity of 28,700 *MW* (**as per GWEC data, [2]**). With an aim to achieve 60 *GW* of wind energy by 2022, lots of work need to be carried out in this sector. These include exploring the new locations for the installation of the wind farm, exploring new heights for capturing maximum amount of kinetic energy of the wind, developing new and sophisticated equipments to harness maximum energy, and determination of favourable wind direction for the installation of the wind farm that can capture most frequent wind speeds available in nature.

The characteristics, as mentioned above, are some of the prime requirements that lead to drawing the attention of the researchers in the wind energy sector.

Installation of the wind farm required huge capital investment. Therefore, accurate assessment of wind resources at the planning and development stages are of utmost importance before installing the wind farm because a single wind turbine, if it is installed, has to deliver the desired performance during its service life, which is more than 20 years. Therefore, wind turbines need to be designed in such a way that along with capturing the maximum kinetic energy of the wind with high conversion to power generation, it should also have the capability to withstand in the varying wind climatic conditions, for the successful production of energy from the wind farm. The wind is having an erroneous behaviour that varies continuously with space and time. Therefore, the assessment of wind resources is essentially required at the initial phase, i.e., at the planning and development stage before the installation of the wind farm.

1.1 Wind Resources Assessment

Wind resources assessment requires the understanding of the behaviour or flow pattern of the wind that enables in the estimation of the availability of wind as fuel for wind power generation. The wind behaviour can be understood based on wind data available, topographical (roughness, obstacles, and terrain), and meteorological (e.g., atmospheric stability, boundary layer structure, weather system) features of a given site **[3]**. In recent years, an advent increase in the size of the wind turbine leads to it an exposure to much more complicated and vulnerable environment condition, especially, different boundary layer structures. Simplified engineering models, which worked well before, have to be re-examined based on the study of wind power meteorology.

Therefore, the extent of accuracy involved in the wind resources assessment at the planning and development stages will lead to the profitable outcome of the installation of the wind farm.

Several available tools, employed for wind resources assessment, are broadly classified into three categories, namely, Numerical Modelling, Analytical Modelling and Statistical Modelling. Numerical Modelling involved the Computational Fluid Dynamics (*CFD*) techniques, Wind Atlas Analysis and Application Program (*WAsP*) technique, etc [3]. However, According to **ISO 4354:2009(E) [4]**, *CFD* models are inappropriate for simulating peak wind speed. Hence, numerical solutions may not be suitable for wind climate modelling. Analytical Modelling uses certain set of equations to model wind shear, such as logarithmic law, power law, horizontal speed-up profile etc. However, the solutions of these equations are restricted to specific assumptions. On the other hand, the Statistical Modelling uses the probabilistic approach. Among these three, the statistical modelling is predominantly used due to its certain advantages for wind resources assessment. Owing to its stochastic nature, the statistical analysis of wind becomes an important pillar for wind resource assessment. As because wind statistics is the science that describes the patterns of the wind regime over considerable time **[3]**. The wind data are usually measured at 10 *m* height all around the world. However, the recorded data are usually contaminated by local features, inconsistent with time, and insufficient measurement points which in turn reduces the quality of the recorded data. Therefore, to overcome such hindrances, long-term data are the essential prerequisite for statistical analyses. In this study, the importance of taking long-term data for wind data modelling has been explained using the following example:

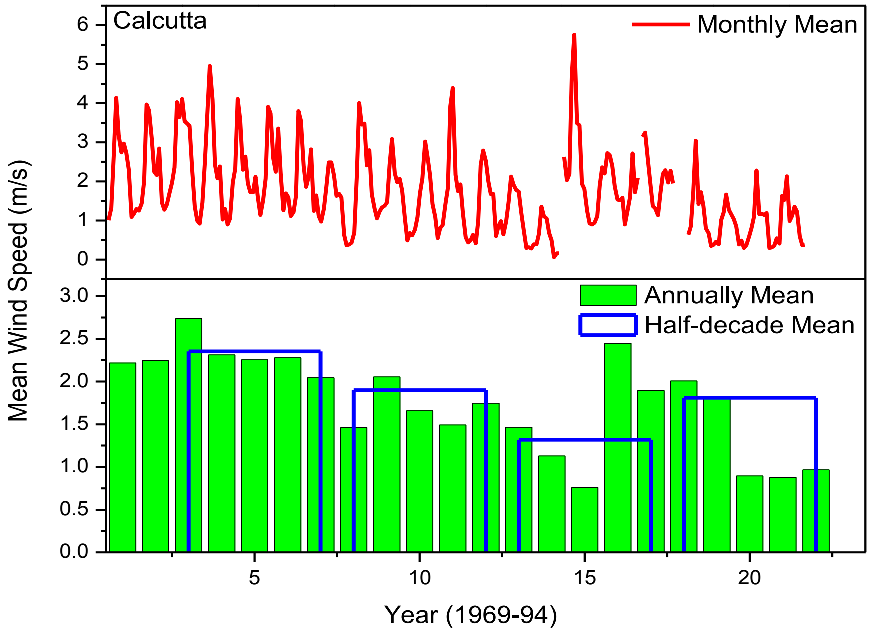

Figure 1.1: Mean wind speed variation for Calcutta.

The fluctuating behaviour of the monthly mean wind speed is shown in the upper frame of Figure 1.1. It is seen from the Figure 1.1 that the mean monthly wind speed varies between approximately 0.05 to 6 *m/s*. However, this fluctuating behaviour of wind speed degraded when annual mean wind speed were taken, as shown in the lower frame of the Figure 1.1. Still there exists lack of stability in the behaviour of the wind speed. However, when the half-decade mean were taken the chances of achieving stability increases. Therefore, long-term data is the essential prerequisite for the accurate judgment about wind resources assessment. In the language of statistics, the wind flow pattern is unstable in the short term. However, it has a regular and stable pattern in the long-term. The long-term wind data behaves as a continuous random variable; therefore, the continuous probability distribution also known as the probability density function (*pdf*) were used to model the predictable pattern of the wind data. The pdf of a continuous random variable describes the relative likelihood for this random variable to take on a given value **[5]**.

1.2 Wind Power Density ($\overline{WPD}$)

The goal of a wind resource assessment is to calculate the amount of wind energy convertible by the wind turbine. Wind power density is the ability of the air mass to convert its kinetic energy into useful power generation; wind power density shares the direct relationship with the economic potential viability of the wind farm. The higher the value of $\overline{WPD}$, more is the economic potentiality of the wind farm. Accurate information about the wind power density can enable in selecting the region for wind power projects. The mathematical expression of $\overline{WPD}$ can be defined as the kinetic energy of the wind per unit area per second (A = 1; t = 1); thus

$$\overline{WPD} = \frac{1}{2}\rho\overline{v^3} \tag{1.1}$$

Empirically, it can be estimated using the expression given below:

$$\overline{WPD} = \frac{1}{2}\int_0^{\infty}\rho v^3 f(v)dv \simeq \frac{1}{2}\sum_{i=1}^{n}\rho v^3 f(v) \tag{1.2}$$

The expression for theoretical estimation of $\overline{WPD}$ based on Weibull distribution is given as:

$$\overline{WPD} = \frac{1}{2}\rho s^3\Gamma\left(1+\frac{3}{k}\right) \tag{1.3}$$

where ρ is the air density, v is the wind speed, and $f(v)$ is the probability density function, k is the shape parameter and s is the scale parameter of the Weibull distribution. This probability density function is a statistical tool commonly being employed to estimate $\overline{WPD}$. The $\overline{WPD}$ indicates the energy potential in the wind of the site.

Based on the value of $\overline{WPD}$, the energy potential of wind can be categorized as:

Table 1.1: The categorization of the wind power density **[3]**

Category	**Wind power density (W/m^2)**
Poor	Less than 250
Fair	250~400
Good	400~600
Excellent	Greater than 600

1.3 Parent Wind Climate Modelling

Wind resources assessment includes the estimation of the wind load density as well as the wind power density, as both are equivalently important for the installation of the wind farm. The wind load density helps in assessing the fatigue failure of both turbine tower and turbine blades. Natural wind flow can cause fatigue failure of the slender structures, which occurs due to the periodic vortex shedding. If the frequency of the periodic vortex shedding matches with the natural frequency of the structure, significant crosswind vibration will cause damage to the structure as well as the turbine blades. On the other hand, the wind power density helps in the conversion of kinetic energy of the wind into a useful form of energy production. It enables the selection of potential sites for the installation of the wind farm and the selection of a suitable wind turbine for a given site. Therefore, correct assessment of these two aspects of wind is significantly important. According to regulatory work **IEC 61400-12 [6]**, the 2-parameter Weibull distribution is the widely used and recommended distribution for describing the wind regime for wind power generation.

A particularly salient feature of the Weibull distribution is that if the wind speed follows the Weibull distribution with shape parameters k and scale parameter s, the load and power density also follow the same distribution with shape parameter '$k/2$' and '$k/3$' respectively, and scale parameters 's^2' and 's^3' respectively **[7, 8]**.

1.4 Wind Turbine Characteristics

The wind turbine characteristics is an important feature that enables the selection of wind turbine at a given site. There are mainly three features namely, Availability Factor, Capacity Factor, and wind turbine efficiency (Power Coefficient) that are used to define the characteristics of the wind turbine.

1.4.1 Availability Factor

Availability Factor is a measure of the reliability of a wind turbine or other plant. It refers to the percentage of time that a plant is ready to generate power, i.e., not out of service for maintenance or repairs. It can be said that Availability Factor is the ratio of total hours of operation of the plant during the period to the total length of the period (hours). Modern turbines have availability of more than 98% higher than most other types of power plant. Nowadays wind turbines are highly reliable.

1.4.2 Power Coefficient (C_p) /Efficiency of the Wind Turbine

It is the ratio of power output from the wind turbine to the input power of the wind. This C_p is a function of wind speed (v). The turbine power curve determines the power output. The output power of a wind turbine is the product of normalized output power to the rated power. The expression of output power is:

$$P_e(v) = P_\mathrm{r}\begin{cases} 0; & v < V_c \\ P_n(v); & V_c \le v \le V_r \\ 1; & V_r \le v \le V_f \\ 0; & v > V_f \end{cases} \tag{1.4}$$

The expression for C_p is

$$C_p = \frac{P_e(v)}{P_{total}} \tag{1.5}$$

where P_{total} is the input power of the wind define as the product of wind power density (see Eq. 1.1) and the swept area of the blade.

1.4.3 Capacity Factor (CF)

Capacity Factor is the ratio of average power output to the rated power output**.** It is a mathematical tool to investigate the most suitable commercially available wind turbine for a given site. Theoretically, the average output power (P_{avg}) of a wind turbine can be calculated by the integration of the product of power output to the pdf.

The wind turbine average power output is given as:

$$P_{avg} = \begin{cases} 0; & v < V_c \\ \int_{V_c}^{V_r} P_e(v)\, f(v)dv; & V_c \le v \le V_r \\ \int_{V_r}^{V_f} f(v); & V_r \le v \le V_f \\ 0; & v > V_f \end{cases} \tag{1.6}$$

The base equation for CF is:

$$CF = \frac{P_{avg}}{P_{rated}} = \int_{V_c}^{V_r} P_n(v)\, f(v)dv + \int_{V_r}^{V_f} f(v)dv \tag{1.7}$$

The above-mentioned wind turbine characteristics are three features that play an important role in selecting the speed parameter of the wind turbine viz., cut-in, rated, and cut-out wind speed of the turbines. Among three, the CF and the C_p are two features that can be theoretically determined using statistical concept, whereas Availability Factor depends on the design specification of the blade, material used in turbine manufacturing, etc. Therefore, the present study emphasizes on the theoretical estimation of the *CF* and C_p of the wind turbine that enables in optimization of design rated wind speed of the wind turbine.

1.5 Extreme Wind Climate Modelling

The tower and blades of the wind turbine are subjected to wind force by the oncoming wind. This wind force also known as wind load is a function of the density of air and design wind speed. The selection of appropriate design wind speed depends upon two criteria viz., the types of structures or to be more precise, the service life of the structures and the climatic condition at that sites. The climatic condition such as thunderstorm, monsoon gale, cyclones, etc. comes under extreme wind climate. These extreme wind climates can be modelled using extreme value distributions. There are three types of extreme value distributions (*EVD*) that are commonly available viz., type I Gumbel distribution; type II Fréchet distribution, and type III Reverse Weibull distribution. The selection of wind speed data for extreme wind climate modelling is a challenging task and is a matter of research as the approaches available for selection of extreme data have certain drawback associated with it. The approach for the selection of wind speed data has been discussed in details of chapter 7 of the current work.

1.6 Wind Direction

Wind direction also plays a vital role in harnessing the wind power from the wind turbine. It is futile to assess wind resources based on wind speed without consideration of the wind direction. The wind direction enables an estimation of the most frequent wind direction encountered in nature for a given site that enable to solve two purposes, viz., it detects the most frequent zone of the wind flow that enables in the installation of the wind farm. Another advantage is that it helps in the installation of the overhead transmission lines, which is always laid in the perpendicular direction of the most frequent wind flow direction, so that the maximum heat dissipation can occur through the transmission lines.

1.7 Outline of the Thesis

Chapter 1 introduces the current wind energy scenario of India, the roadmap ahead to achieve the desired target of converting a nation into a sustainable source of energy particularly in the wind energy sector. The area yet to be explored for maximization of electricity production. The significance of wind resources assessment lies in harnessing the wind power potential from the kinetic energy of the wind.

Chapter 2 presents a comprehensive evaluation of various continuous distributions from the application point of view to harness power from the kinetic energy of the wind. Several continuous distributions used to describe unimodal, bimodal, bitangential wind data, and the methods employed to estimate their parameters have been reviewed and duly compared based on several goodness of fit statistics. Analytical models that are used to define the wind turbine characteristics, namely, CF and C_p have been studied. The research gap, objectives of the work, and contribution of the thesis work have also been discussed.

Chapter 3 presents the discussion about the wind speed recording technique adopted by IMD, Pune, and the error occurred due to the adopted sampling technique. This technique results in the biased estimation of parameters of the distribution, thereby, leads to an inappropriate estimation of wind power potential. The chapter deals with the eradication of error generated by recording technique and enables in the estimation of unbiased Weibull parameters that are free from errors.

Chapter 4 proposed a new method by the name of Modified Energy Pattern Factor (*MEPF*) method and compared the same with six popular methods to estimate the Weibull parameters. The advantage of *MEPF* is that it is free from binning as well as iterative procedures. All methods have been compared via Monte Carlo simulation study with sample sizes varying from 100 to 100,000 as well as long-term data collected from sites. The results indicate that the *MEPF* method is a viable alternative and is comparable with the relatively best estimator of the Weibull parameters at each sample size.

Chapter 5 proposes a novel turbine performance index (*TPI*) which can take into account the monthly averages of the wind speed data and enables in the evaluation of the optimum rated turbine speed ($V_{r,opt}$) for a given site. To verify the applicability of this novel approach, various types of commercially available wind turbines have been assessed for two different representative hub heights.

Chapter 6 presents the assessment of long-term wind speed data with higher parameters distributions also known as mixture distributions. These mixture distributions have an advantage that it can be used to model heterogeneous wind speed data. Their applicability to Indian wind speed data has rarely been done. Therefore, this chapter deals along with proposing new mixture distributions namely Truncated Normal-Gamma and Gamma-Gamma distribution, compared the same with others mixture distributions such as Weibull-Weibull, Gamma-Weibull, Truncated Normal-Weibull, Truncated Normal-Normal, and *MEP* based distribution to model Indian wind speed data, so that the accuracy to model wind speed data can be improved.

Chapter 7 presents extreme wind climate modelling using a new approach that combines the merits of both ‘block maxima’ and ‘peaks over threshold’ approaches, to determine the design wind speed. The extreme peaks over the appropriate threshold value have been fitted into the generalized *EVD* (Type-I, II, and III) and compared the same with conventional Generalized Pareto Distribution. The five plotting position formulae have also been compared in this chapter.

Chapter 8 presents the wind direction assessment using new 4-parameter Kato-Jones distribution and compared the same with conventional 2-parameter von Mises distribution, and finite mixtures of von Mises distribution to determine the most suitable wind direction for installation of the wind farm.

Chapter 9 presents the conclusions as well as the future scope of the research work carried out in this thesis.