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Studies on Wind Power Installation for Domestic Load in Urban Settings

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Abstract

The increased energy demand owing to upgraded living standards world-wide has opened new spheres for electric power generation. The coupled quest of generating more electricity and protecting environment has evolved into an engineering challenge to design conversion systems - environmentally benign and cost-effective. The mandate of United Nation's Sustainable Development Goals (SDGs) envisages addressing significant areas of concern that directly impact the quality of human life. The SDGs targeted for the year 2030 cover all critical areas of concern, including- poverty, hunger, clean water, gender equality, global peace and affordable and clean energy. The 17 goals in the purview of the UN mandate emphasize Goal 7 as vital in supporting other goals. The SDG-7, titled 'Clean and affordable energy', targets eco-friendly technologies that fuel developmental activities and simultaneously protect the interests of future generations in terms of a sound ecosystem. Renewable energy is primarily the driving force for future energy needs, as evidenced by the new power installations installed worldwide. Government policy has been congenial in promoting renewable energy that poses several technical challenges to make them feasible for large-scale implementation.

Major Findings: *The selected site is assessed to have good wind potential, with 5.342 m/s of average wind speed, making domestic wind power viable for tailored to loads. The study evidenced annual energy production variations, with an average of 14,796 kWh and a standard deviation of 876.4 kWh. Finite Element Analysis (FEA) was employed to design turbine components and assess structural integrity. The results indicated safe operation under various loading conditions.*

Keywords: *Finite Element Analysis, Structural Analysis, Wind Statistics, Wind Turbine*

1.0 Introduction

The wind energy does not produce any pollutants during operation as it does not consume any fossil fuels to liberate green-house pollutants like carbon-dioxide and smoke. The net emissions are marginally small as it operates on renewable source. The wind power aligns with SDG-7: Affordable and Clean Energy and manifests as a key solution to get sustainable energy mitigating global climate crises. Its adoption lowers greenhouse gas emissions, contributing to reduced effects of climate change, and improved energy independence. The wind energy has benefits that include features of- renewable nature, low operating cost and minimal environmental impact, lowered carbon footprint, lower cost per kWh compared to fossil fuels that are associated

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with pollution menace and high carbon footprint. This makes it possible for wind-energy to contribute significantly in transiting to clean and renewable energy future.

The modern wind turbine adopts aerofoil blade geometry to build adequate surface-fluid interaction to capture kinetic energy in natural streams of air, referred to as wind. The wind turbine system delivers continuous rotary mechanical output power that finds utility in electricity generation or other processes like water lifting or grinding operations. Wind formation and intensity depend on several factors, such as solar energy intensity, presence of water bodies and complex ground structures, and vegetation covering ground surface. The wind speed magnitude plays a vital role due to its cubic relation to generated power for a linear rise in wind speed. The wind speed increment from 1 to 2 m/s produces an eight-fold surge in available wind power. Therefore, importance placed on site choice strongly affects overall system performance and rate of return on investment. The wind speed and its periodic variation cycle is a dominant factor in its viability as dependable energy source. The extreme wind speed magnitude also influences intensity of loads encountered by wind turbine structures at the location. These factors decide selection or choice of wind turbine parameters that include cut-in, rated and cut-out speeds. The specificity of wind turbine to prevailing wind pattern at the location is reflected by the term called 'Plant Capacity factor' that indicates a valuable fraction of wind power plant. The Capacity factor directly influences annual energy accumulated by wind power plants and directly linked to turbine specifications and site wind pattern (Weibull parameters- c and k). Hence, the choice of wind turbine for a specified location is not a mere choice of aesthetics and economics, but is deeply rooted into net energy delivered annually or seasonally. The operational characteristics of the turbine blade include Coefficient of power (Cp) that is influenced by the direction of wind interception by blades, which necessitates for Orientation device.

The upper limit of C_p for an ideal frictionless bladed turbine is restricted by the Betz limit of 59.27%, which indicates a maximum theoretical wind turbine efficiency of 59.27%. This constraint is due fluid dynamics limitations of not extracting entire kinetic energy contained in wind. The Betz limit in turbine design enables engineers to assess the performance extent of actual system against this theoretical limit, and direct innovations toward greater efficiency within these physical constraints. The deviations of wind turbine performance are attributed to operational parameters in operation under climatic extremes like of snow-fall, thermal expansion at high operating temperature, biological infestation by fungi of micro-organisms, localized blade deformation due to lightening strikes. The improper blade and wind stream surface-fluid interaction builds higher frictional resistance leading to drop in Cp value for turbine blade. The segmental drop in aerodynamic forces reduces overall torque of blade structure as per 'Blade Element Momentum theory'.

The design of wind energy conversion device has a clear focus on aerodynamics and climatic factors. The pattern of wind speed variation with altitude or height above ground surface is governed by 'power law'. The optimum tower height on basis of investment on tower structure to additional gain in turbine power is made on basis of this inter-relationship. The wind tower is an essential component in the WEC system that ensures the exploration of higher wind speeds by placing the rotors at higher altitudes. The changes in magnitude of wind speed above ground surface as a function of altitude above ground is proposed by one-seventh power law. The tower structure experiences myriad loading states, including forces induced by wind speed, bladed rotor, nacelle, and generator.

The selection and structural design of WEC system are presented with a detailed analysis of the tower structure using a numerical approach. The investigations based on numerical approach of Finite Element Analysis (FEA) adopts the strategy of 'part to whole study' to get an insight into static load studies.WEC systems in current usage strongly suggest adopting intelligent systems that can ensure a faster return on investment by prior assessment of the site and design of optimum geometry of turbines responsive to prevailing wind conditions at the specified location.

2.0 Literature Review

The usage of renewable wind resource to power various activities has been witnessed for ages back to the period when Persians and the Chinese harnessed it to grind

grain and lift water. In the 14th century, the Dutch used wind power to dry their lands. In the 19th century, small windmills were installed in the United States. The first-ever wind energy turbine to produce electricity was installed in the US with a load range of 0.2 to 3 kW, producing 32V. The development of wind energy has gone from 48 to 433 GW between the years 2006 and 2017. In India, the development began in Dec 1952 by CSIR (Council of Scientific and Industrial Research) in Saurashtra and Coimbatore. A small-scale wind energy plant was installed at Porbandar in 1962; India now has Tamil Nadu (29% of total energy), Gujarat, Maharashtra, Karnataka, and Rajasthan as the top 5 leading states in wind energy generation; India now ranks fourth in terms of installed capacity worldwide with a capacity of 47.7 GW with capacity factor between 25% to 45% at national level.

The energy contributed from wind resource ranks high among all other renewable energy contribution making it a popular contender in clean energy power generation. The wind turbine with constituent parts like foundation, tower, yaw control, generator, rotor blade, gearbox, brake and modern-day safety devices functions as a sustainable means to power the growing economies[1]. The wind turbine tower height extends from the ground surface to hub height owing to wind speed variations and experiences drastic changes in loading pattern. The changes are observed during normal operating conditions and during storm conditions. This wide range of change patterns necessitates an appropriate design strategy to optimize the material usage without sacrificing the safety aspects of the overall structure. The cyclical variations in rotor position relative to the tower induce variation in loading pattern, producing fatigue loads during operation[2]. A sub-assembly failure leads to the failure of the assembly. Failure of the tower structure is the reason that leads to the failure of wind turbines[3]. Unscheduled failure leads to maintenance and, in turn, causes a huge power loss[4]. The main objective is to maximize wind energy utilization through reasonable control of wind turbines and provide steady support through the towers.

Katinka Johansen reported on the evolution of the wind energy sector in Denmark through an environmentally sensitive energy policy formulated as a cooperative movement keeping conventional nuclear energy at bay. The strong lessons of the Danish energy policy were thoughtful for implementation at the global level to promote renewable energy to a greater extent and save the planet Earth from the vagaries of climate change and global warming. The author traces back the history of wind energy technology, such as the primitive wind turbines in the late 18th century, the energy crisis of the 1970s, and the generation of environmental awareness that shaped a policy that laid prime focus on sustainability. The article gave a comprehensive account of challenges in implementing renewable energy and societal solid support for low-carbon energy generation. Other nations can adopt the practices of the Danish community to make a difference at the global level in terms of mitigating carbon emissions in support of the clean energy generation goal[5].

Jamie Baxter *et al.*, have reported on the societal mindset to accept wind energy as an alternate energy based on data collected between 2010-2018 concerning research initiatives in Community Wind Energy (CWE) projects. The study puts forth two key segments that include process adopted and process output related which are correlated with practice and research to promote wider acceptance of wind energy at the community level. The community level wind power, as fraction of total energy consumed has been extensively investigated to identify challenges faced by policy matters. The study observes that wind energy installation as a green energy initiative must speak about the electric energy contributed at the community level to gain wider acceptance. Promoting wind energy at the community level requires the participation of social scientists who build a link between technology and its acceptance. The study established the need to develop amiable solutions at the community level to gain societal ownership in the detailed backdrop of economics, societal benefits and historical energy context[6].

Bartłomiej Iglinski *et al.*, have comprehensively reviewed wind power generation in Poland from historical, present and future perspectives. The study established that the nation had a long tradition of using wooden wind turbine installations due to power generation economics. The Institute of Meteorology identified Poland's southwestern, central and northern regions as potentially windy sites based on data collected at 100 m height from the ground. The ambitious Renewable Energy Sources Act had brought in congenial growth prospects for wind

energy evolved through a detailed SWOT analysis for developing an economically feasible model for investors[7].

John K. Kaldellis *et al.*, have reported that wind energy exploitation dated back to five thousand years was out of energy scenario due to abundant fossil fuel usage. Wind energy usage was renewed worldwide owing to the shift in global policy to generate green energy based on sustainability practices. The journey of wind energy development to modern-day off-shore installations that target to attain total installations of 1000 GW by 2030 has been presented. The study highlighted the revival of wind energy during the last 30 years, prospects and challenges towards reaching the target, and global perspectives on wind energy[8].

John K. Kaldellis presented introductory concepts related to wind energy power generation, highlighting its pros and cons from the perspective of replacing conventional energy. The limitation of wind energy of being site-specific to make it suitable and economically viable only at specified locations with adequate wind potential necessitates a thorough investigation before installation. The aspects of the current state of technology developed in wind energy conversion devices, along with future research directions to introduce unique features demanded by the new generation, will form the bedrock to promote wind power in a big way. Wind power was foreseen to be of enormous potential, albeit due to technical challenges of developing low-speed wind turbines capable of yielding a higher capacity[9].

Aliaksandr Novikau reported on prospects of wind energy in Belarus that had limited wind potential owing to being geographically land locked and restricting wind to a lower speed. The low wind speed potential necessitated unique wind energy conversion devices that ensured break-even generation to meet the minimum revenue requirements. The power generation sector in Belarus was a plain field of competition, with different players like nuclear energy and conventional energy sources competing with the renewable energy sector. The recent developments in the global arena have raised the alarm towards avoiding over dependence on imported crude oil, shifting focus on harnessing Indigenous wind potential. However, wind energy development in the nation faced stiff competition from nuclear power, amounting to the withdrawal of preferential subsidies and reduced feed-in tariffs for wind-generated electricity[10].

Virtanen E. A. *et al.*, reported on developing a novel approach to offshore wind potential assessment considering environmental, societal and economic factors in the true spirit of sustainable development. The investigations were made in Finland based on high-resolution spatial data that is valuable in protecting environmentally sensitive regions. The sluggish growth of on-shore wind power was attributed to poor social acceptance and ecological constraints, leading to higher growth in the off-shore version. The ecologically sensitive areas are to be avoided entirely for wind power installations, and an informed study based on spatial data was an effective means to aid the selection process. The spatial prioritization integrated high-volume data to provide informed decisions that cover concerns of all sustainability parameters linked to 'cradle to grave-carbon footprint' associated to wind power generating system. The spatial data covered 150 data layers at 100 m resolution in the coastal region of Finland to explore offshore installations over 81,500 km^2 of the marine region. The procedure adopted can be extended to make similar investigations in other areas to ensure minimum impact on the environment[11].

Artur Santa Catarina has discussed the economic aspects related to Brazilian wind power projects from 2009 to 2019 in terms of the levelized cost of energy. After investigations on 758 projects, the study concluded that projects with scales above 31 MW performed poorly in terms of the levelized cost of energy computed based on two different taxation modes. The study concluded that taxation policy would bring most installations into an economic crisis, as opposed to the auction price average, pushing renewable energy policy into jeopardy. Thus, the success of wind power installation being operated under varying conditions of power availability needed a supportive energy policy to become competitive[12].

3.0 Methodology and Approach

The study highlights the design of wind power systems for a specified load for domestic applications devised for urban locations. The design strategy includes the assessment of characteristics of wind data for power generation and selecting a suitable location for its implementation. The configuring of blade geometry follows the principles of

fluid flow to minimize aerodynamic-drag to facilitate air motion to generate high order lift force by account of its asymmetric geometry. The lift force generated by air circulation along the blade shows variations at different segments of rotor blade, exhibiting magnitude that is directly proportional to blade area and to square of resultant wind speed. The resulting lift component on each element of blade contributes an elemental torque with direct variation on basis of radial distance from rotor axis. All elemental blade torques collectively add up to generate rotor torque, leading to mechanical rotary power linked directly that third power of resulting wind velocity vector on the rotor blade and decided by prevailing wind pattern at site. Mechanical power is transformed into electricity through a generator that can be used for various utilities, such as electric lighting and mechanical drives, such as motors and pumps. Thus, through appropriate energy conversion devices, wind power can meet energy needs to meet all sorts of power requirements. Hence, wind energy is identified as a sustainable power source for designing an energy system with a defined energy load that can include thermal, electrical, and mechanical forms. Hence, the design of the wind energy conversion system involves matching energy needs with wind potential at the site. The complete system design of wind energy conversion is a multidisciplinary study that needs structural studies along with electrical component design. The transformation of wind's kinetic energy into rotary mechanical power is termed the 'Coefficient of Power'-Cp, measured as the ratio of mechanical power output to input wind power. The limit of the power coefficient is based on the geometry, relative position of the blade chord and wind vector, and surface characteristics of the blade surface. The Betz limit with a magnitude of 0.593 defines maximum limit for the transformation. The wind turbine gains larger input energy when the turbine's plane faces the wind in the normal direction. Hence, the wind energy conversion devices use orientation and regulating mechanisms. The energy the wind turbine can accept is limited by the blades' and the tower structural load-bearing capacity. The modern day wind energy converter if facilitated with a series of sensing elements to pick data of prevailing wind speed, vibration level of entire structure, wind direction, voltage and current levels at generation station and grid side, power-factor, and rotor speed. The measurement systems located at top region of Nacelle captures data of speed and direction of prevailing air current. This data acts as a precursor to actuate electronic controller to modify turbine operating variables like speed, blade pitch angle and rotor plane position relative to existing wind direction. The system operates in a feed-back mode generating 'error signal' owing to presence of discrepancies in operating state-points. The deviation in wind direction actuates the yaw-motor to turn the Nacelle to facilitate rotor plane position to receive wind in normal direction with respect to rotor plane of spinning. Similarly, the changes in magnitude of wind speed triggers the blade pitch controlling mechanism to immediately set its pitch angle to optimum value to ensure a smart or intelligent manipulation of operating states of wind energy conversion device[13]. The wind data of the location provides valuable information on available wind potential at the area and acts as a pre-requisite for wind power installations. There are different instruments for wind speed predictions, among which Weibull statistics and Monte-Carlo simulation were considered for the present study.

The structural analysis includes selecting the appropriate size for the turbine rotor and tower structure for the wind energy converter adopted for domestic loads. The proper dimensions of the turbine blades and tower structure make it suitable for extracting the necessary power from the wind available at the location. Therefore, appropriately matching wind potential with existing load is essential for designing an energy system. The investigations are done based on the real-time wind speed and load to meet the domestic electric energy needs of a typical 12-hour day. Using statistical tools to predict load and wind speeds makes it possible to synchronize source and demand.

4.0 Analysis and Discussion

The results obtained concerning site investigations and the structural design of wind energy conversion systems are presented as part of the investigations. The aspects related to site selection and structural analysis of wind turbine systems form the initial phase of project implementation.

4.1 Weibull Statistics for Wind Prediction

The Weibull distribution is the widely used two-parameter probability distribution function to predict wind speed

at specified locations. The parameters include scale (c) and shape (k). The probability distribution function in mathematical form can be expressed as calculations indicated below.

Probability distribution Function

$$f(u)=\left(\frac{k}{c}\right)\left(\frac{u}{c}\right)^{k-1}\exp\left[-\left(\frac{u}{c}\right)^{k}\right]-----(1)$$

Cumulative Probability distribution Function

$$F(u)=1-\exp\left[-\left(\frac{u}{c}\right)^{k}\right]--------(2)$$

Average wind speed

$$u_{avg}=c\Gamma\left(1+\frac{1}{k}\right)----------(3)$$

Standard deviation of wind data

$$\sigma^2=c^2\left[\Gamma\left(1+\frac{2}{k}\right)-\Gamma^2\left(1+\frac{1}{k}\right)\right]----(4a)$$

$$\sigma^2=u_{avg}^2\left[\frac{\left(1+\frac{2}{k}\right)}{\Gamma^2\left(1+\frac{1}{k}\right)}-1\right]------(4b)$$

Power available in wind

$$\mathrm{P_w}=\frac{1}{2}\rho\mathrm{A}\int_0^{\infty}\mathrm{u^3f(u)du}--------(5a)$$

$$P_w=\frac{\rho A u_{avg}^3\Gamma\left(1+\frac{3}{k}\right)}{2\left[\Gamma\left(1+\frac{1}{k}\right)\right]^3}----------(5b)$$

Energy produced by turbine

$$W_{\max}=\frac{1}{2}\rho A u_{me}^3 f(u_{me})\times 8760-----(6)$$

Average turbine power:

$$P_{e,avg}=\mathrm{P_{eR}}\left[\frac{e^{-(u_c/c)^k}-e^{-(u_R/c)^k}}{(u_R/c)^k-(u_c/c)^k}-e^{-(u_F/c)^k}\right](7a)$$

$$P_{e,avg}=\mathrm{P_{eR}}(CF)=\eta_o\frac{\rho}{2}Au_R^3(CF)---(7b)$$

Wind speed of maximum energy extraction

$$u_{me}=c\left(\frac{k+2}{k}\right)^{1/k}----------(8)$$

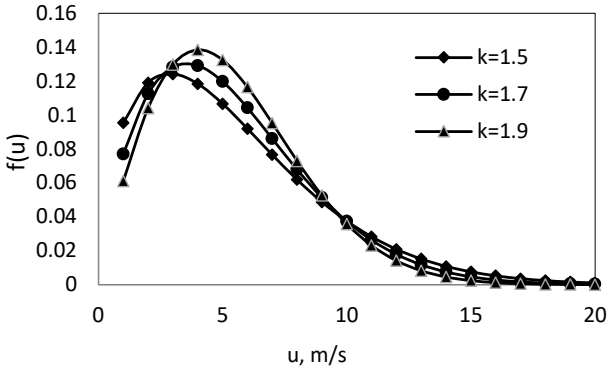


Figure 1. Weibull distribution at u=6m/s for different k.

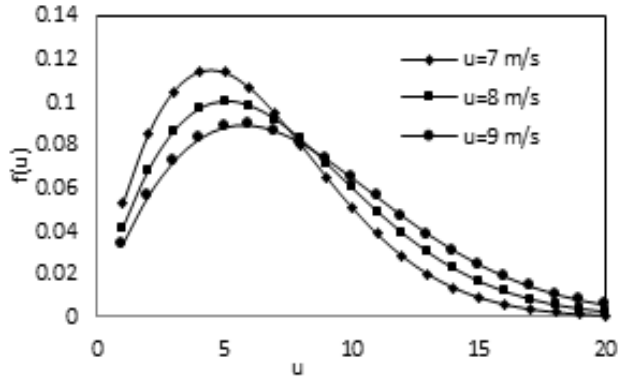


Figure 2. Probability distribution for constant k=1.8.

Weibull scale factor (c)

$$c = \frac{u_{avg}}{\Gamma(1+(1/k))} \text{----------(9)}$$

Weibull shape factor (k)

$$k = d_1\sqrt{u_{avg}} \text{----------(10)}$$

The results of wind turbine simulations are indicated by Figures 1 to 5 and discussed in this section. The Figure 1 indicates wind speed probability variation for different values of weibull shape factor (k)- 1.5, 1.7 and 1.9 signifying changes in the occurrence of uni-modal peak towards higher wind speeds for greater values of k. The shift is also associated with narrowing of velocity distribution for higher shape function that is theoretically greater than unity ranging up to 2.4 for locations with higher average wind speeds. The location average wind speed (u_{avg}) is directly proportional to weibull parameters of scale factor (c) and shape factor (k).

The Figure 2 shows probability of wind speed for constant k of 1.8 with parameter 'c' changing from 7 m/s to 9 m/s in steps of 1 m/s. The trend indicated that higher values of 'c' gave the uni-modal peaks to shift towards higher wind speeds with diminishing value of peak probability distribution f(u). The variation is a clear indicator of selection of sites with higher 'c' factor for identical 'k' factor prevailing at multiple sites.

The Figure 3 highlights cumulative probability distributions F(u) observed for constant 'c' of 6 m/s and varying 'k' parameters with highest value of 'k' reaching the velocity distribution faster compared to lower values of 'k' justifying the choice of locations with larger 'shape factor'.

The distributions in Figure 4 shows cumulative probabilities of wind speeds observed for constant wind scale parameter of 1.8 with increasing magnitude of weibull scale factor ('c'). The earlier observations made in Figure 2 are reiterated, indicative of higher 'c-value' for location to be more beneficial among the existing set of locations contending as potential wind power installation sites.

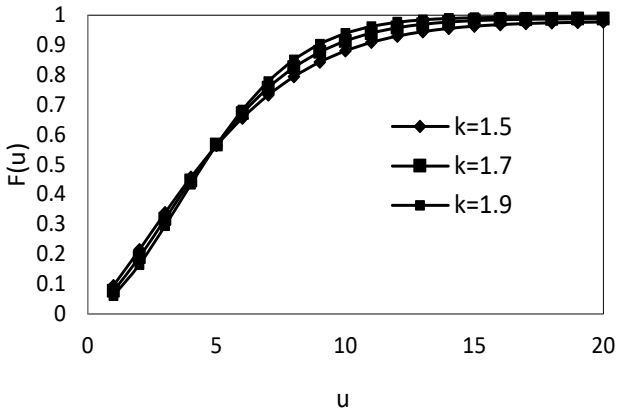


Figure 3. Cumulative probability, 6 m/s for different k.

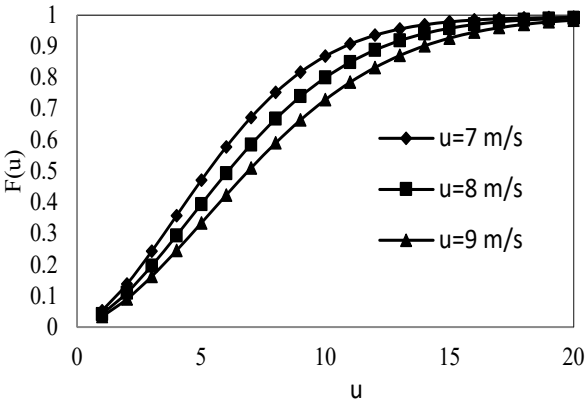


Figure 4. Cumulative probability at wind speeds.

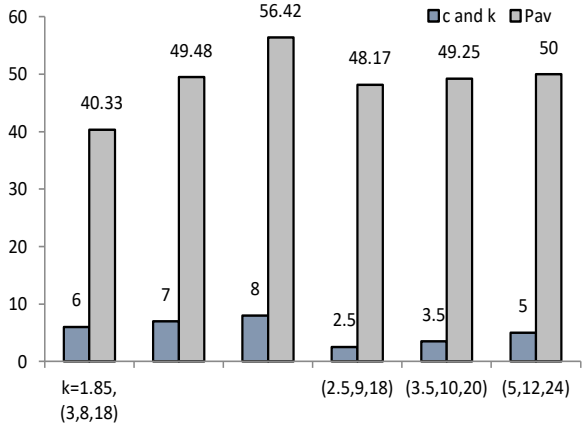


Figure 5. Variation of Avg-power with weibull parameters.

The observations in Figure 5 depict the changes in average power extracted from six turbine-site combinations installed with constant parameter k= 1.85 and changing 'c' parameter between 2.5 m/s to 8 m/s. The wind power peaked at 56.42 kW for (3,8,18) turbine for c=8 m/s, as against lowest value of 40.33 kW observed with same turbine for c=6 m/s indicating drop by 28.51% in average power extracted. The collective data of six combinations had standard deviation in extracted power as 5.15 kW. The data clearly emphasized role of suitable choice of wind turbine specification to match the site wind pattern, a poor selection led to un-economical business proposal due to reduced electricity generation.

4.2 Monte-Carlo Simulation

The Monte-Carlo simulation technique is based on the fact that wind distribution at a location is repetitive, and the long-term history of wind speed at the location can be utilized to predict wind speed. The wind data forms a frequency distribution that is adopted to define the range of random numbers to a particular wind speed based on 4-digit or 5-digit random numbers that respectively have numbers (0000-9999) or (00000-99999) to cover the entire cumulative frequency from 0 to 1.00 represented by various wind speed frequencies. Thus, it can be observed that more random numbers get assigned to wind speed with the highest frequency. A true random number generator is a computational aid that usesan unbiased set of random numbers.

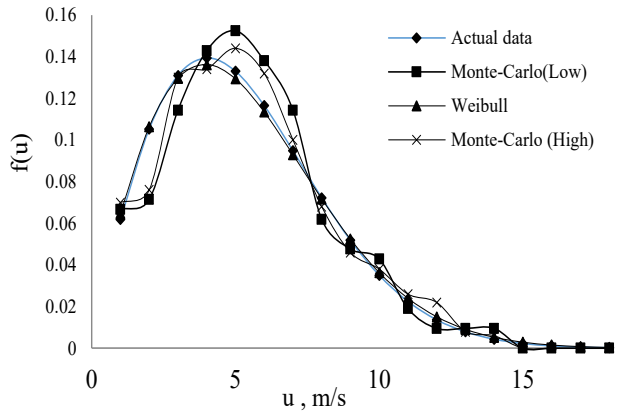


Figure 6. Simulations and Actual wind data.

If it is required to predict the 8760 hourly average wind speeds during the year, an equal number of random numbers are generated. Each random number maps with a particular wind speed per the defined random number distribution.

The simulation-based on 210 data points was generated using the Monte-Carlo technique to predict the wind speed at the location as depicted in Figure 6. As the number of data points were taken at intervals of wind speed in 1 m/s, deviations between actual data and the simulations based on the Monte-Carlo technique were observed. The increase in the data points from 210 (low) to 500 (high) leads to the distribution approaching closer to the actual data. The data showed an average wind speed of 5.32 m/s against Monte Carlo simulated averages of 5.447 m/s and 5.436 m/s, considering lower and higher data points indicated in Figure 6 that highlighted that more number of data points leads to lower deviation from actual data. The deviations in mean wind speed at the location are 2.027% and 2.23%, respectively, in the case of high data and low wind speed data.

Thus, the future occurrence of wind speeds at a location can be made effective by adopting Weibull distribution or Monte Carlo simulation. The accuracy of prediction is governed by the quality of wind data collected at the location. Wind prediction in long-term or short-term terms gains importance from the point of view of designing various strategies for load management and sizing system components.However the Weibull statistical model is a better wind prediction model based on two parameters of wind speed distribution termed as scale factor (c) and shape factor (k). These parameters fit more to the stochastic nature of wind behavior. The Monte Carlo method shows great variation in predicted wind speeds (they are closer when larger datasets are used) despite its good functionality on random distributions. This limitation of break-even volume of data limits Monte-carlo simulation usage and justifies Weibull distribution to bemore accurate, especially in both long-term wind predicting and also wind turbine site selection.

4.3 Load Data Analysis

The electrical or mechanical utility that consumes generated power from the wind power system is referred as

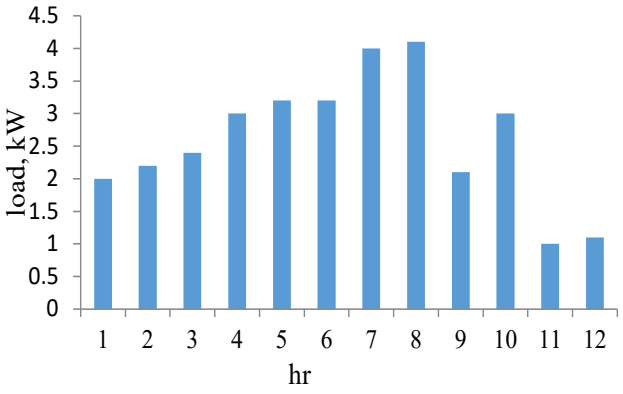


Figure 7. Load curve -Domestic consumer.

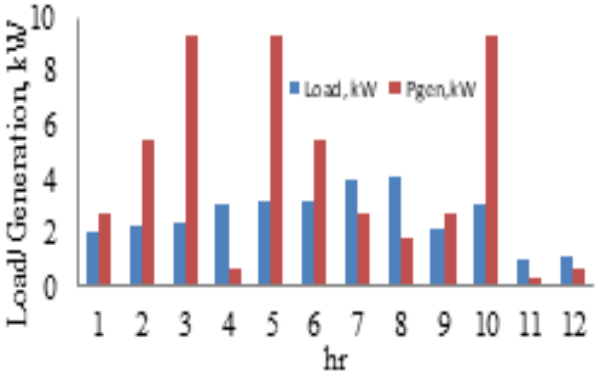


Figure 9. Load and generation data.

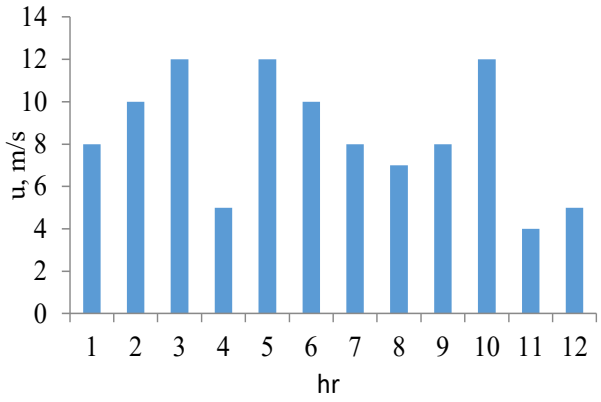


Figure 8. Daily Wind speed variation.

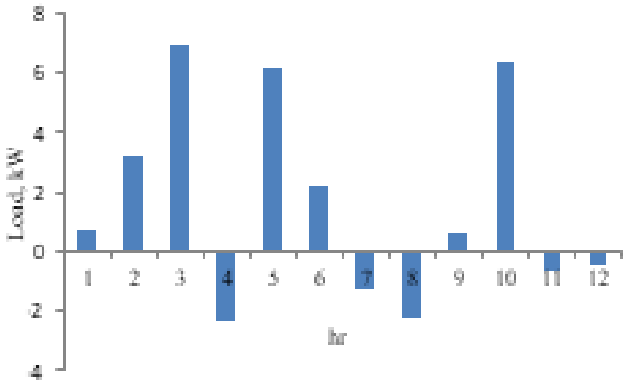


Figure 10. Load and Generation Deviations.

load. As long-term storage of power generated is difficult or expensive, matching the generation with consumption is always beneficial. This strategy is the 'Load analysis' and involves extensive monitoring of the two ends of power train. The Power conditioning devices function in matching consumer needs with supplier capacities to ensure minimum losses in load and reliability of power supply.

The selection of wind turbine generator depends upon the anticipated load that is expected to be catered through the generation system. The Figure 7 shows graphical indication of hourly consumer load defined in terms of kW over the 12 hour period during a typical day. The maximum load is 4.1 kW occurring at time of 8.00 hr while the lowest load was recorded as 1.0 kW situated at 11.00 hr. The average load was estimated as 2.60 kW with a standard deviation of 0.994 kW over the 12 hour period of load variation.

The Figure 8 shows the variation in the wind available at the location over the same 12 hour duration when the anticipated load curve was plotted. The frequent changes were observed in the wind speed pattern, peaking at 12 m/s with minimum speed of 4 m/s exhibiting an average value of 8.41 m/s at a standard deviation of 2.84 m/s recorded during a typical 12 hour observation period.

The study matches resource available with the anticipated load through the data collected during the study duration.

The Figure 9 combines the data of load information with the possible wind power generation utilizing the resource available at site. The data shows certain durations

of mismatch in available generation and power consumed in 12 hour observation period. The study indicated a mix of both surplus power and deficit power when both information of load and generation were superimposed. The data compiled clearly stated need of intermediate energy storage device to match demand of power to supply obtained from renewable resource.

The Figure 10 indicates relative durations of surplus and deficit power for wind based power generation system connected to a isolated electric load. The 12 hour period of observation showed a shortfall in power during five instances, while power available exceeded consumption during seven instances in the 12 hour investigation period. The information gathered from load curve analysis provided a clear understanding on need of additional power or possibility of additional load inclusion into system.

4.4 Sizing of WEC System

The power output of a wind turbine depends on turbine swept area, the turbine power coefficient and the operating wind speed. The wind turbine specification includes cut-in, rated, and cut-out speeds, which respectively indicate wind speeds to initiate power generation, generate rated power, and stoppage of wind turbine. The wind turbine selection parameters includes diameter, kW rating and type of control mechanism. The fixed-bladed or variable-pitch wind turbines are possible options during the selection, with higher costs associated with the latter version due to the sophisticated controls adopted. The selection thus depends upon wind patterns at the location and the cost of alternate power sources. The data gathered through Weibull statistics or Monte-Carlo simulation techniques greatly aid site selection in catering to the required load. The overall output energy collected by a wind power generation system is called 'Energy production' and is obtained as the product of average power and time duration. As the instantaneous power delivered by wind turbines depends upon various climatic factors like wind speed, air density, and turbine specifications, its magnitude keeps varying. The average magnitude is evaluated as the product of the system rated power and Capacity Factor (CF).

The start-up, rated, and furling velocities of a wind turbine are critical parameters that determine its productive operation. Power output is zero for wind speeds below the start-up speed, increases from start-up to rated speed, remains constant at rated power between the rated and furling speeds, and drops to zero beyond the furling speed. The relationship between wind speed and power generation is represented by the turbine power curve.

The efficiency of a wind turbine over a specific period (daily, monthly, or yearly) is quantified by its Capacity Factor (CF), which depends on the wind characteristics-described by the Weibull parameters (scale parameter c and shape parameter k)- and the turbine's design specifications.

Turbine selection based on these critical speeds is standard practice. The start-up speed marks the minimum wind speed for power generation, the rated speed corresponds to maximum power output, and the furling speed indicates the threshold at which the turbine ceases operation to prevent damage. In urban areas, where wind speeds are generally low, turbines with lower start-up and moderate-rated speeds are preferable, ensuring higher energy efficiency and operational reliability under varying wind conditions. Thus, energy production depends heavily on the capacity factor, which reflects the interplay between turbine specifications and wind patterns.

4.5 Alternate Designs of Wind Energy Plant

The wind-based power generation opens up various design possibilities for wind turbines, gearboxes, generators, energy storage devices, controllers, and power conditioning. The study investigates alternate options for generating electric power to meet a peak load of 4.5kW to be installed in urban settings with a lot of surrounding high-rise residential buildings. The surrounding buildings influence the flow pattern of air and, thereby, the available wind input to the system. Normally, the range of wind speeds in urban settings is lower compared to open spaces with minimum obstructions for air movement. Hence, the design of domestic wind turbines involves a modified version of the wind rotor with a lower cut-in speed and moderate value of rated speed.

The alternate designs conceived to meet the required load conditions include:

S-1: L-shaped lattice tower, Speeds of Cut-in - 4m/s, rated - 8 m/s and cut-out - 18m/s, 5 kW generator at 300 rpm;

1:6 gearbox and 10 kg overall weight;

S-2: Aluminum-concrete tower, Cut-in - 3m/s, rated - 6 m/s and cut-out - 15 m/s,4.5 kW generator at 600 rpm;

1:6 gearbox,10 kg overall weight;

S-3: L-shaped lattice tower, Cut-in– 2.5 m/s, rated - 9 m/s and cut-out - 20m/s,5 kW generator at 600rpm;1:6gear box;

S-4: Aluminum-concrete tower, Cut-in - 2m/s, rated - 10 m/s and cut-out - 20 m/s,4.5 kW generator at 800 rpm. ;

1:6 gear box, 10 kg overall weight;

S-5: L-shaped lattice tower, Cut-in –1.5m/s, rated - 7.5 m/s and cut-out - 16m/s,5 kW generator at 800 rpm;

1:6 gear box, 10 kg overall weight.

Based on the average wind of 5.32 m/s Weibull parameters are c=5.96 m/s and k=1.9

capacity factor and energy production data are compiled in Table 1

The energy production data of 5 versions of wind turbine units exhibit variations in the magnitude of annual energy production, which is highest for S-3 and lowest for S-4. The study revealed that the appropriate choice among the five alternate designs can be further based on economic parameters like cost per kWh of generation and the payback period obtained.

The rated power of turbine reflects its highest output and identified as important specification for selection of turbine for a specified load. The higher rated power demands large turbine size of turbine or availability of higher average wind speed at location. The structural design of wind turbine demands a heavier rotor to sustain larger aerodynamic loads, while also increasing the cut-in speed. On the contrary the capacity factor is a metric that reflects duration of total operating time when the wind power generation is at rated power rating. The capacity factor for a wind turbine (cut-rated-furling speed) installed at a location with wind pattern (c,k) depends upon the relative compatibility. Capacity factor, gives the amount of power actually generated over a period compared to the power that would be produced if the system were performing at rated capacity continuously and provides a measure of efficiency and productivity in wind energy.

4.6 Structural Design of Turbine Components

The typical wind energy conversion system can be presented as a schematic diagram in Figure 11, showing wind rotor connected to the gearbox through the low-speed shaft. The generator draws power from the gear box at an appropriate speed and torque level. The Power train consists of WT: Wind turbine, GB: Gearbox and Gen: Electric Generator connected by LSS: low-speed shaft and HSS: high-speed shaft. The Wind turbine rotates.

Design aspects of low-speed and high-speed shaft of all five alternate designs + Turbine diameter calculations

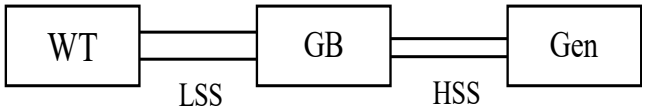


Figure 11. Wind system power Train

Table 1. Energy production and data of alternate designs

Type	S-1	S-2	S-3	S-4	S-5
$(u_c u_r u_f)$	4,8,18	3,6,15	2.5,9,20	2,10,20	1.5,7.5,16
N,RPM	300	600	600	800	800
P_{eR}, kW	5	4.5	5	4.5	5
CF	0.352	0.349	0.352	0.352	0.351
E_{annual}	15442	13787	15453	13908	15391
Day avg	42.30	37.77	42.33	38.10	42.16

Table 2. Sizing of alternate designs

Type	S-1	S-2	S-3	S-4	S-5
LSS Dia	28.35	21.73	22.51	19.74	20.45
HSS Dia	14.43	11.05	11.45	10.04	10.40
D_{Rotor}m	8.00	11.68	6.70	5.42	8.80

The diameters of LSS and HSS are evaluated based on magnitudes of power and torque transmitted by the shafts. The estimation of shaft diameters is based on the following data and material properties.

Shear strength of shaft material (f_s) =300 MPa; Generator efficiency :90%; Gear box efficiency: 80%; Gear ratio:1/6

The equation for diameter is given by the expression,

$$D_{shaft} = 2 \times \left[\frac{2T}{\pi f_s} \right]^{1/3} \text{----------(11)}$$

The rotor diameter for wind turbine is based on the expression of power extracted by wind turbine at rated speed and Coefficient of power (C_p) for turbine rotor. The Power extracted by wind turbine is based on the equation,

$$P_{turbine} = \frac{1}{2} \rho A u_r^3 C_p \text{ ---------- (12)}$$

$$A = \frac{2P_{turbine}}{\rho u_r^3 C_p} = \frac{\pi}{4} D^2 \text{ ----------(13)}$$

$$D = \left[\frac{8P_{turbine}}{\pi \rho u_r^3 C_p} \right]^{0.5} \text{ ----------(14)}$$

The rotor diameters for the five models indicated lowest value of 5.42 m for design S-5 owing to its rated speed of 10 m/s, while design S-2 exhibited a rotor diameter of 11.68 m for a lower rated speed of 6m/s. The turbine blades are constructed of light weight material to ensure their operations at smaller cut-in wind speeds and tough enough to withstand loads imparted at higher speeds during operation in limits of rated and furling velocities. The commercial wind turbines adopt fibre-reinforced polymer material for construction.

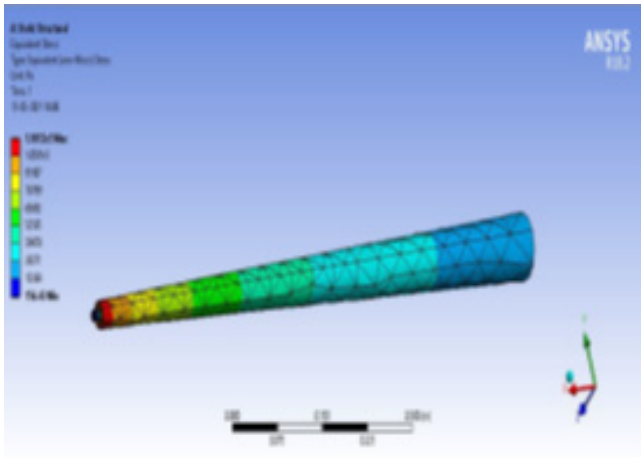


Figure 12. Turbine tower -structural study in FEA tool.

The rotor shaft gets connected to generator shaft through the gear-box shaft with entire structure housed in the casing termed as "Nacelle" which is mounted on tower structure. A large or elevated tower structure ensures access to higher wind speeds as per the wind speed power law that relates local wind speed with height above ground reference. The cost of the tower also becomes a deciding factor in fixing up its dimensions. Selecting suitable materials for wind turbine towers is part of the structural design of wind energy conversion systems[14]. The tower uses standard structural steel grades S235, S275, S355 and S450. The S275 grade material is incorporated into the conical tower model investigated. The tower model was imported for static structural analysis, which was performed using an ANSYS workbench to analyze performance characteristics. The structural modelling estimated deformation and stress distribution in wind turbine tower. The Figure 12 indicated, equivalent Von-

Mises stress induced into tower structure to highlight occurrence of tower failure predominantly due to localized buckling.

The conical standard wind turbine tower exhibited a minimum Von-Mises stress, with a maximum stress of 1.1812 x 10^5 Pa and a minimum of 156.43 Pa. The overall investigations based on computational studies indicated safe operation with design considerations.

5.0 Conclusions

The modern-day wind energy converter has intelligent features to transform naturally available air stream into rotary mechanical power and subsequently to obtain electricity. Using wind energy as a substitute for fossil fuels is suitable for promoting sustainable energy. The prediction of wind patterns at the location has been reported to be more accurate for Weibull statistics compared to the Monte-Carlo technique. The selected area has a good potential for wind speed with an average of 5.342 m/s and makes a good location for wind power installation. The match between wind potential and electric load at the defined site is satisfactory, and efficient means to store produced electricity is essential to minimize deviations between produced power and consumed power. The turbine selection constitutes vital decision in wind power extraction at identified site and is characterized by its functional specifications of start-up, rated, and furling velocities. These parameters along with intelligent device control mechanism are decisive in electric power generation form wind power. The computational tools based on FEA open up new opportunities to investigate refined blade and rotor geometries to ensure high strength to weight capabilities in blade design. The five alternative designs investigated showed that average energy production of 14796 kWh, with standard deviation of 876.4 kWh for the observed annual production. The thorough investigation of site and design aspects of wind conversion systems can ensure development of sustainable alternatives to fossil-fueled power generation.

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7.0 Data Availability Statement

The authors confirm that data in support to research findings are presented in the article. The raw data supporting the findings are available with corresponding author upon written request

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