Wind Energy : A Practical Power Analysis Approach

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***Abstract*— Wind energy is one of the fastest-growing green technologies as it provides clean, safe, and renewable electricity generation. This study provides insights into the available methodologies for sustainable power harnessing using wind resources , scrutinizing the developments in the recent decades and the future potential of global wind power industries. Contrasting and comparing the expected Weibull distribution to the true frequency distribution of the actual wind speed, this research proposes an empirical equation using Polynomial Lasso Regression techniques over field data obtained from Turkey, for the instantaneous active power generated by wind turbines in practical scenarios. A detailed overview of the wind energy calculation and improvements is discussed with the existing wind power production techniques. Finally, an optimal analysis of wind power utilization in top Indian states, and inspection of potential wind power applications is carried out with respect to the Indian subcontinent.**

Keywords*— *Wind Power Analysis, Renewable Energy, Sustainable Development, Wind Turbines, Lasso Regression, Instantaneous Active Wind Power, Weibull Distribution, Frequency Distribution of Wind Speed

I. Introduction

Today's overpopulation requires a plethora of energy sources, often constrained by the utilization of fossil fuels, petroleum, gas, coal, and atomic power[1]. The world has to keep up to 80% of our natural energy resources on the earth in order to keep our global average temperature below 1.5 ° C- however, our reliance on these products is widening worldwide[2]. As it is well known that fossil fuels have limited potential and they are expected to deplete within centuries due to this current rate of exploitation.

These non-renewable sources pose major threats to the entire human race, such as drastic pollution and global warming, and also their limited availability adds more significance to the use of renewable energy sources as an alternative for the future generation. Renewable energy sources need to be harnessed for socioeconomic growth & development and it is at the forefront of the global priority of addressing climate change.

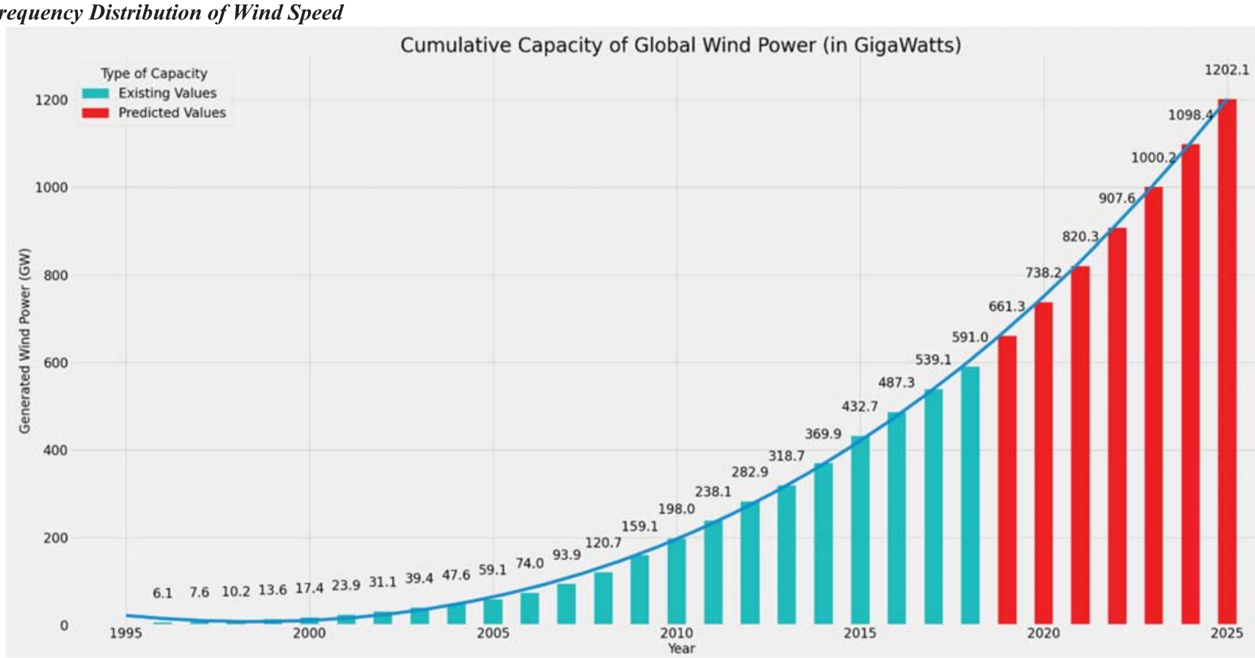

Fig. 1. Cumulative Capacity of Global Wind Power (in Gigawatts): Progressive Development of Wind Power Production over two decades. (Predictions made using Polynomial Regression.) [5]

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Green technologies are considered crucial in such an environment and wind energy is the plausible sustainable development innovation. Wind energy is one of the most advantageous renewable energy sources and it is targeted as one of the largest energy contributors for future power supply.

In the past few decades, from an alternative energy source wind energy has become a new fast growing industry[3]. It is trusted that, as the most encouraging energy source, wind energy is the best option to diminish the interest for non-renewable energy sources. In this study, we attempt to shed some light on the stages of production of wind energy using wind turbines and provide an in-depth analysis of wind power generation with mathematical modelling.

II. Global Wind Power Production: Developments

Since the advent of modern wind power production technologies which originated from Denmark, these industries became a global economy, progressing rapidly [4]. Assessments using polynomial regression over the previous scientific growths in the wind energy sector estimate the global wind power to shoot up to 1200 Gigawatts in 2025[5].

The impressive trends in wind energy production from the mid-1990s are displayed in Fig. 1. Although lots of development is still required to utilize this precious environment-friendly resource, the world is progressing steadily over improving this vast field of sciences. The curve is clearly rising since the initialization of this innovative energy resource.

III. Wind Energy: An Asset

Wind power can be obtained with the change in horizontal air movement in both direction and magnitude parallel to the earth's surface, often termed as the wind. Wind turbine rotors capture and convert this wind power into mechanical power which in turn gets converted into electricity by the generator. The way we power our world – in a safe, clean and sustainable manner– becomes profoundly vital with the study of the special characteristics of wind power generation, because of its many advantages:

- Eco-friendly and non-toxic source of energy generation which provides sustainable development with economic growth.
- Clean and naturally available source of energy.
- Immense potentiality to generate large-scale electricity for industrial and domestic applications.
- Developed modern technology usage in wind turbines have created cheaper and advanced control systems leading to optimized capacity turbines, thereby increasing efficiency, feasibility & economic viability.

IV. Wind Generation :

Wind is generated by a combination of three concurrent naturally occurring events, viz., Uneven heating of the atmosphere by the sun, Surface Anomalies over the Earth, and Rotation of the Earth [6]. Wind turns a turbine's propeller-like blades around a rotor, which spins a generator and ultimately produces electricity.

V. Wind Frequency: The Weibull Distribution

The wind follows a natural frequency distribution called the Weibull Distribution[7]. The radiation from the sun is absorbed by the earth's surface and then returned to the atmosphere. It gives a huge impact on wind speed. The Weibull distribution is a statistical model defined by two parameters, which can be altered to change the scale (λ) and the shape (k) of the curve. It describes the probability of the occurrence of different wind speeds[8]. Weibull distribution provides additional flexibility to fit an observed wind-speed histogram.

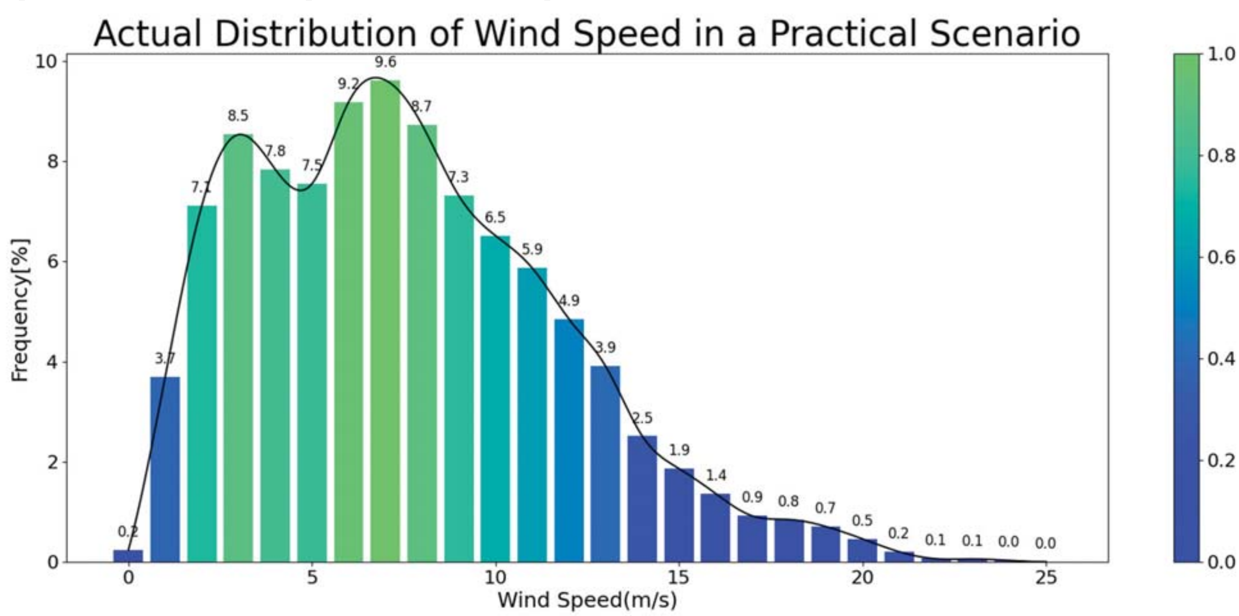

Fig. 2. Actual Distribution of Wind Speed in a Practical Scenario [9]: Plotting the percentage frequency for each Wind Speed (0-25m/s) for the wind turbine field data.

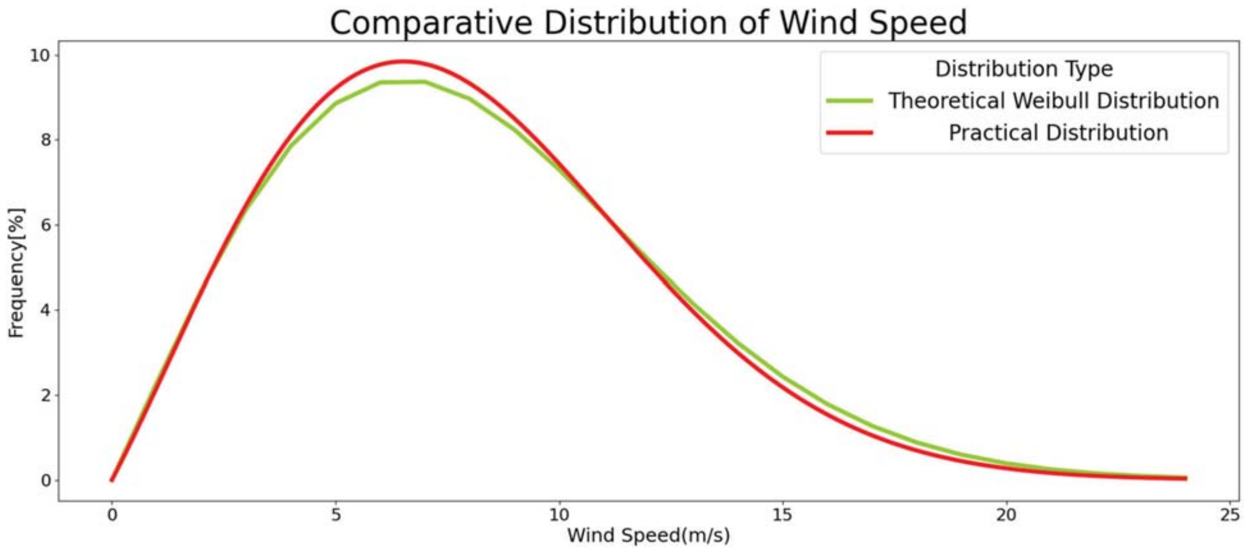

Fig. 3. Comparative Distribution of Wind Speed [9]: The Theoretical Weibull Distribution vs the Practically Obtained Distribution. Clearly the practical distribution deviates from the expected ideal behaviour.

The probability density function of a Weibull random variable is:

$$f(x;\ \lambda, k) = \begin{cases} \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-(x/\lambda)^k} & x \geq 0 \\ 0 & x < 0 \end{cases} \tag{1}$$

where $k > 0$ is the shape parameter and $\lambda > 0$ is the scale parameter of the distribution. We fitted our dataset to the Weibull Distribution [10][11] and obtained a significant deviation from the same as portrayed in Figures 2 & 3. (k = 2.08 and λ =8.97m/s, with average wind velocity v_{mean} =7.88m/s) [9].

VI. Wind Power Production: Methodology

A wind turbine transforms wind energy into electricity using the aerodynamic force from the wind-driven rotor blades. As wind flows through the blade the air pressure decreases on one side of the edge. The difference in air density between the blade's two sides produces lift as well as drag. The lift force is stronger than the drag which causes the rotor to spin. The rotor is attached with the generator either directly (if it's a direct drive turbine) or via a shaft and a series of gears (a gearbox) that accelerate the rotation and allow for a physically smaller generator. This conversion of aerodynamic force to rotation of a generator creates electricity [12].

Generally, wind turbines fall into two basic categories:

- Horizontal Axis Wind Turbine (HAWT): They are the most commonly used turbines due to their strength and efficiency. They have three blades and operate "upwind," with the turbine rotating at the top of the tower so the blades face into the wind. The rotation of the blades can generate more wind power compared to the vertical axis wind turbine.
- Vertical Axis Wind Turbine (VAWT): These turbines are omnidirectional and they are less affected by the frequent change in wind direction compared to horizontal axis wind turbines because here the blades are rotated on the rotor shaft perpendicular to the ground.

VII. Wind Power Calculation:

The Betz's Law provides the following equation for Theoretical Wind Power (Instantaneous) [14]:

$$P_{wind}(t) = \frac{1}{2}\rho S v_1^3(t)\left\{1 - \left(\frac{v_2(t)}{v_1(t)}\right)^2 + \left(\frac{v_2(t)}{v_1(t)}\right) - \left(\frac{v_2(t)}{v_1(t)}\right)^3\right\} \tag{2}$$

Simplified Maximum Theoretical Wind Power [14],

$$P_{wind}(t) = \frac{1}{2}\rho S v^3(t) \tag{3}$$

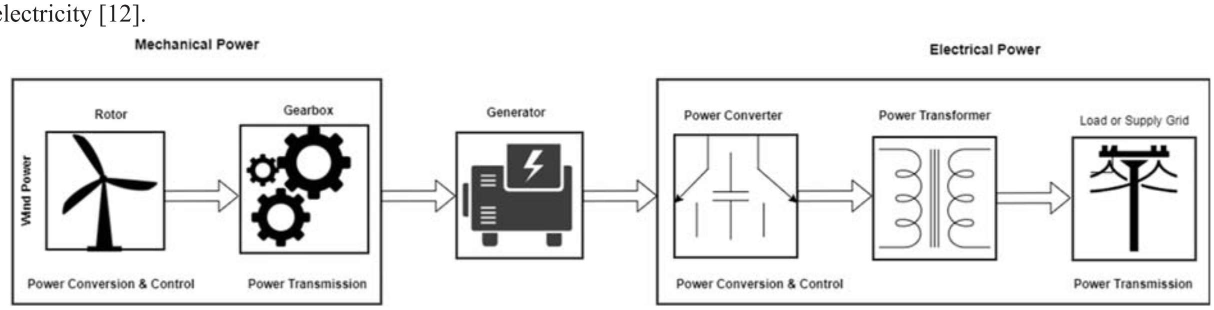

Fig. 4. Working Principle of Wind Turbines: A Schematic Diagram [13]

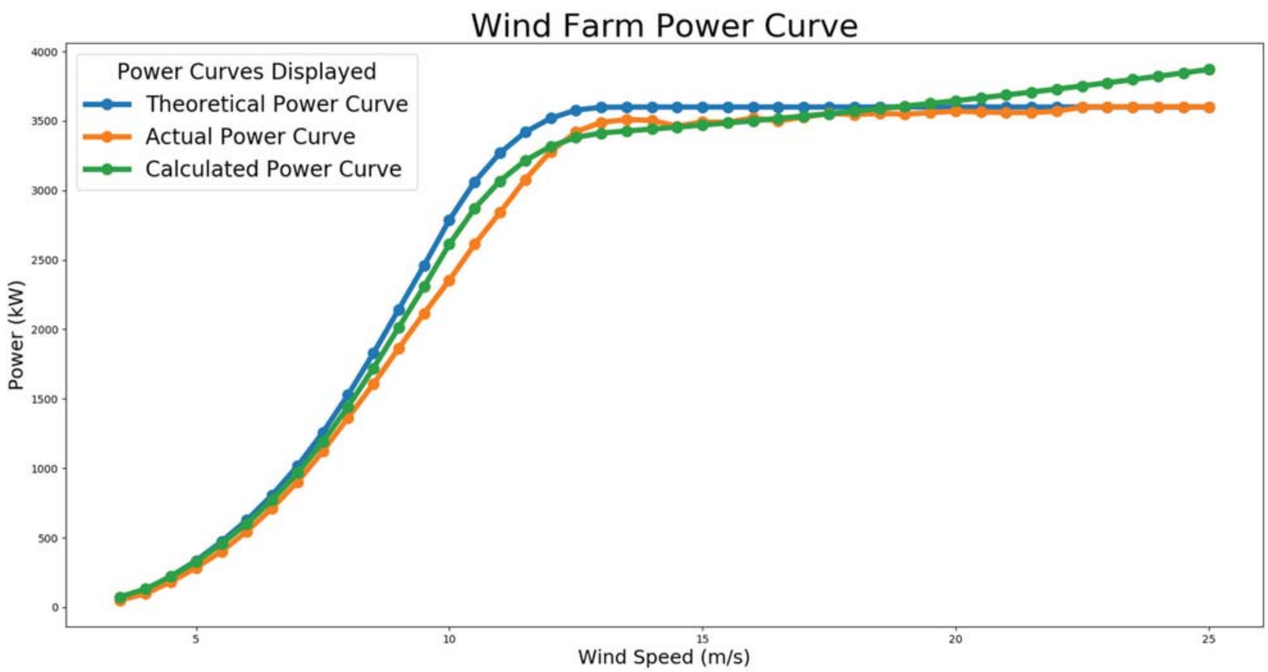

Fig. 5. Wind Farm Power Curve: The Calculated Regression Power Curve is very close to the Actual Power Curve [9].

where $v_1(t)$ is the speed upstream of the rotor, $v_2(t)$ is the speed downstream of the rotor, $v(t)$ is the speed of fluid power device (average of upstream and downstream rotor speed), $v(t) = \frac{1}{2}\left(v_1(t) + v_2(t)\right)$
where S is the surface area of the turbine, A_1 and A_2 are the areas of fluid before and after reaching the turbine, the density of air $\rho = 1.23kg/m^3$.
If we differentiate $P_{wind}(t)$ w.r.t. $\frac{v_2(t)}{v_1(t)}$, we can get the maximum value of $P_{wind}(t)$. The result is that $P_{wind}(t)$ reaches maximum value when $\frac{v_2(t)}{v_1(t)} = \frac{1}{3}$.
Substituting this value in the results,

$$P_{wind}(t)_{max} = \frac{16}{27} . \frac{1}{2}\rho S v^3(t) = C_p . \frac{1}{2}\rho S v^3(t) \quad (4)$$

where C_p is called Coefficient of Performance [14]. It has a maximum value $C_{p_{max}}$ = 0.593 or 59.3% which is also known as the Betz's limit.

According to Betz's law, wind turbines can never be better than 59.3% efficient. It states that the maximum power that can be extracted from the wind is independent of the design of a wind turbine. The law can be simply explained by considering that if all of the energy coming from wind movement into the turbine were converted into useful energy then the wind speed afterwards would be zero. But, if the wind stopped moving at the exit of the turbine, then no more fresh wind could get in - it would be blocked. The improved [15] equation for theoretical wind power is given by,

$$P_{theoretical}(t) = \frac{1}{2} C_p N_g N_b \rho S v^3(t) \quad (5)$$

where ρ is the air density in kg/m^3 , S is rotor swept area in m^2, $v(t)$ is wind velocity in m/s, C_p is Coefficient of Performance, N_g is generator efficiency, N_b is gear box bearing efficiency.
Most of the research already done in the field of Wind Power Generation provide a good insight into the Theoretical Wind Power, but the Actual (Instantaneous) Wind Power although being, close to the Theoretical Curve has no definite formula till date. From the dataset [9] of the Wind Farm we fitted a Positive Coefficient Polynomial Lasso Regression Curve to the dataset (Fig 5.) and obtained the following empirical expression:

$$P_{actual}(t) = \alpha \times P_{theoretical}(t) + \beta \times v^2(t) \quad (6)$$

$$P_{actual}\left(v(t)\right) = \frac{\alpha}{2} C_p N_g N_b \rho S v^3(t) + \beta \times v^2(t) \quad (7)$$

The values of the constants obtained were $\alpha = 0.9013$ (dimensionless) and $\beta = 0.7172\, kg/s$. This gives us more intuition about the Instantaneous Power delivered by the turbine at a given point of time. Fig 5. shows the fitted regression curve, which is a good approximation for the Actual Power for Wind Speed values between 0-20m/s. One limitation of this curve is that the values of $P_{actual}(t) = P_{theoretical}(t)$ for Wind Speeds $v(t) \geq 20\, m/s$. Furthermore, the obtained coefficients tell us that the Actual Power comprises of approximately 90% Theoretical Power and 72% Squared Wind Speed.
Moreover, the Power Loss (Percentage) which leads to the deviation of the Actual Wind Power from the Theoretical Wind Power can be calculated as follows:

$$Loss\ (\%) = \frac{P_{theoretical}(t) - P_{actual}(t)}{P_{theoretical}(t)} \times 100\%$$
$$= \frac{\frac{1}{2}C_p N_g N_b \rho S v^3(t) - (\frac{\alpha}{2} C_p N_g N_b \rho S v^3(t) + \beta \times v^2(t))}{\frac{1}{2} C_p N_g N_b \rho S v^3(t)} \times 100\%$$

$$Loss\ (\%) = \left\{(1-\alpha) + \frac{\beta \times v^2(t)}{\frac{1}{2}C_p N_g N_b \rho S v^3(t)}\right\} \times 100\% \qquad (8)$$

As $\frac{\beta}{\frac{1}{2}C_p N_g N_b \rho S v(t)} \ll 1$, ignoring the second term, we get,

$$Loss\ (\%) \cong (1-\alpha) \times 100\% = \ 9.87\% \qquad (9)$$

This Power Loss of 9.87% plausibly occurs due to frictional forces, wind turbulence disturbances, Wake Effect [16] and other environmental effects. This numerical value gives an approximate estimation of these losses combined together.

VIII. India : Potential of Wind Farms and Uses

Fig 6. displays the Top Indian states with the most satisfying wind energy potential. The potential has been measured on the basis of 3 levels (50m, 80m, 100m) and has been ranked by the total potential of the 3 categories [17]. It is visible that the top 3 states are Gujarat, Karnataka and Andhra Pradesh. If exploited entirely, these states could be a boon for India, and would be eligible for producing energy of at least 60 Gigawatts each.

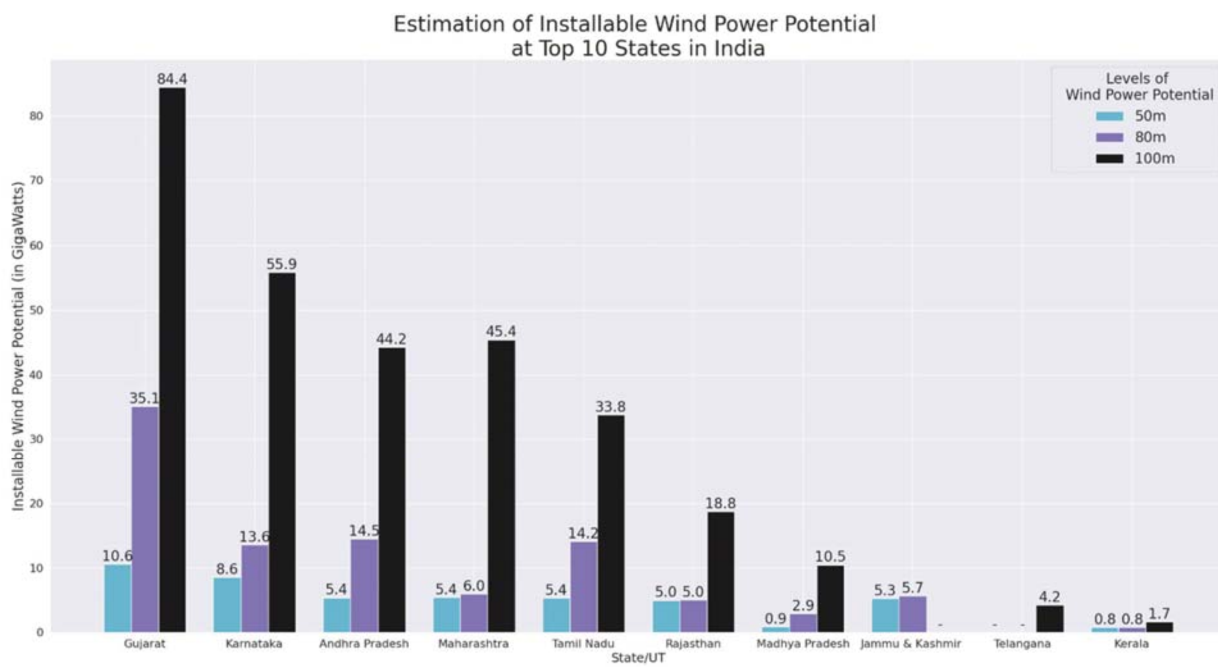

Fig. 6. Estimation of Installable Wind Power Potential at Top 10 States in India: Gujarat being the most yielding if utilized completely [16].

Localized applications of wind power potential in India are as follows:

- Wind energy is utilized for pumping water in rural areas and it's also useful in remote villages. About 20,000 MW electricity can be generated in India using wind energy.
- In large coastal, hill, and desert, wind energy can be carefully utilized for generation of electricity and water pumping.
- Wind energy is also used to propel the sailboats in rivers and seas to transport men and materials from one place to another.
- In flour mills, wind energy is also used to grind the grains like wheat and corn into flour.

IX. Conclusion

A sustainable alternative in the form of renewable energy is vital for rapid progress in the world. This research shows a comparative analysis of the wind power in the ideal and the real case scenarios and provides technical insights into the various possibilities that this field consists. There is always room for more improvement over experimental equations that we provided in this study. Wind energy is the most rapidly growing green industry and will be a primary rich source of renewable power for the globe in the near future. The unlimited wind resources, when utilized at a large scale, will provide technological developments with various innovative opportunities.

This study provides analytical results on practical wind data and further research on statistical formulation of governing equations are yet to be derived by theory. Also, a new parameter for measuring wind energy loss is established and deviations from ideal behaviour of formulae are researched upon for empirical mathematical tests.

All the calculations and visualizations created in this study have been documented and open-sourced for further research. These resources can be found out on github.com/khanfarhan10/wind_analysis.

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