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Forecasting Wind Energy Potential in Chattogram, Bangladesh: Statistical Modeling Incorporating Rayleigh and Weibull Distributions

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***Abstract*—The purpose of this study is to investigate the wind energy capacity in Chattogram, Bangladesh, by using statistical modeling techniques that integrate Rayleigh and Weibull distributions. As the demand for renewable energy rises, wind power is becoming an attractive option for sustainable electricity generation in Bangladesh. Proper evaluation of wind energy potential is needed for effective planning and implementation. We collected historical wind speed data from diverse sources, including scholarly journals, publications, the World Bank, the Bangladesh Renewable Energy Agency (BREA), and the Bangladesh Bureau of Statistics (BBS), and analyzed it using statistical techniques based on Rayleigh and Weibull distributions. By utilizing the data this study aims to predict the potential of wind energy by analyzing the distribution of wind speeds and calculating important factors such as the average wind speed, Weibull shape factor, and scale parameter. We used advanced statistical analysis to examine the regional and temporal variations of wind energy resources of Chattogram. The findings from this study enhance comprehension of the practicality and profitability of wind energy projects in the coastal areas by enabling wellinformed decision-making for sustainable energy development efforts in Bangladesh.**

***Index Terms*—Wind energy, Weibull distribution, Rayleigh distribution, Chattogram**

I. Introduction

Renewable energy sources, such as wind power, are gaining popularity due to global efforts to combat climate change and reduce fossil fuel dependency [1]. Bangladesh shares a similar situation as numerous developing countries since it seeks renewable energy solutions. Wind energy emerges as the chosen solution for sustainability by the country for resolving their energy requirements [2]. Chattogram, a coastal city and major seaport, holds significant wind energy potential due to favorable wind conditions. However, harnessing this requires understanding local wind patterns and their variability. Accurate wind resource estimation aids turbine design, site selection, and energy output prediction [3]. Statistical models, including Rayleigh and Weibull distributions, are vital for analyzing wind data and assessing potential. This study examines wind speed variations in Chattogram using these methods.

Chattogram, the second-largest city in Bangladesh, is a vital economic hub located on the Karnaphuli River near the Bay of Bengal in the southeast. Situated at approximately 22.3569° N latitude and 91.7832° E longitude, it hosts one of the region's busiest ports. Its coastal position results in significant seasonal and regional wind speed variations. During the pre-monsoon season (March to May), moderate to strong winds from the northwest and northeast, ranging from 5 to 15 km/h (3 to 9 mph), provide relief from rising temperatures [4]. This study evaluates historical data to map wind resources spatially and temporally, aiming to characterize wind patterns and estimate key parameters. By integrating statistical modeling with real-world data, it seeks to enhance understanding of wind energy potential and support sustainable development [2]. The findings can guide strategic planning and policy decisions, promoting wind power adoption in Chattogram and beyond.

II. Literature Review

Motivated by the need for sustainable development and energy security, Bangladesh's exploration of wind power plays a vital role in global renewable energy discussions. Wind energy is crucial for transitioning to cleaner energy sources and cutting carbon emissions [2]. With its diverse topography and extensive coastline, Bangladesh holds significant wind energy potential. Studies emphasize analyzing regional wind resources to identify suitable wind farm sites, particularly in coastal areas with consistent wind patterns [2]. Research highlights substantial wind resource potential, especially in southeastern and coastal regions with favorable wind speeds for electricity generation [3]. Mapping these resources is essential for optimal wind farm placement. While wind energy offers a strong alternative to fossil fuels, reducing greenhouse gas emissions and addressing climate change [1], its implementation demands careful planning and strategic investment.

National publications underscore wind power's role in enhancing energy security by reducing reliance on foreign fuels [5]. Beyond environmental advantages, wind farms can stimulate local economies and create jobs [6]. However, challenges such as limited suitable sites, land-use conflicts, grid integration, environmental impacts, and social acceptance necessitate careful planning and stakeholder engagement [7]–[9]. Supportive government policies, like feed-in tariffs, are crucial to encourage investment and unlock wind energy's potential [10]. For Bangladesh, realizing this potential requires addressing these challenges through research and strategic planning. Community involvement and social impact assessments are vital for ensuring public acceptance of wind projects [11]. Studies also stress the need for analyzing grid integration solutions to accommodate wind power [12]. Techno-economic assessments, including cost reductions and turbine advancements, aid investment decisions [13], [14]. Wind resource assessments often employ models like Rayleigh and Weibull distributions, providing critical insights into wind speed patterns and project feasibility [15]–[19].

III. Methodology

We collected data from a variety of sources, including scholarly journals, other publications, the World Bank, Bangladesh Renewable Energy Agency (BREA), and the Bangladesh Bureau of Statistics (BBS). We used the Weibull distribution to analyze wind speed and estimate energy potential. Key variables include wind velocity (W_i), mean speed (W_{mean}), standard deviation (σ_W), shape factor (k), scale factor (c), total number of wind speed intervals (z), total power ($P_{available}$), wind power density ($P_{density}$), most frequent speed (W_{mode}), and maximum power speed (W_{max}) to assess wind resources. Mathematically,

$$W_{mean} = \left(\frac{\sum_{i=1}^{z} f_i W_i}{\sum_{i=1}^{z} f_i} \right)^{1/3}, \tag{1}$$

$$\sigma_W = \sqrt{\frac{\sum_{i=1}^{z} f_i (W_i - W_{mean})^2}{\sum_{i=1}^{z} f_i}} \tag{2}$$

Weibull Distribution:

$$p(W) = \frac{k}{c} \left(\frac{W}{c} \right)^{k-1} e^{-\left(\frac{W}{c}\right)^k}, \tag{3}$$

$$P(W) = 1 - e^{-\left(\frac{W}{c}\right)^k}, \tag{4}$$

$$W_{mean} = c \cdot \Gamma \left(1 + \frac{1}{k} \right), \tag{5}$$

$$c = W_{mean} \cdot \Gamma \left(1 + \frac{1}{k} \right)^{-1}, \tag{6}$$

$$\sigma_W = c \cdot \sqrt{\Gamma \left(1 + \frac{2}{k} \right) - \left[\Gamma \left(1 + \frac{1}{k} \right) \right]^2} \tag{7}$$

Power-Related Quantities:

$$P_{available} = \frac{1}{2} \rho A W_{mean}^3, \tag{8}$$

$$P_{density} = \frac{\rho c^3}{2} \cdot \frac{3}{k} \Gamma \left(1 + \frac{3}{k} \right), \tag{9}$$

$$W_{mode} = c \left(\frac{k-1}{k} \right)^{\frac{1}{k}}, \tag{10}$$

$$W_{max} = c \cdot \left(\frac{k+2}{k} \right)^{\frac{1}{k}} \tag{11}$$

Another helpful method for assessing wind speed data that we used for this study was the Rayleigh distribution, which works well in areas with considerable air turbulence, such as coastal areas like Chattogram.

$$\Phi_m = \chi \cdot \tau \left(\frac{3}{2} \right), \tag{12}$$

$$\chi = \frac{2\Phi_m}{\sqrt{\pi}}, \tag{13}$$

$$\sigma_D = \frac{3}{\pi} \rho A \Phi_m^3, \tag{14}$$

$$\Phi_{mode} = \sqrt{\frac{2}{\pi}} \cdot \Phi_m, \tag{15}$$

$$\Phi_{max} = 2\sqrt{\frac{2}{\pi}} \cdot \Phi_m \tag{16}$$

The Rayleigh distribution variables simplify wind energy analysis: Φ_m is the average wind speed, χ represents wind magnitude, σ_D is wind power density, Φ_{mode} is the most common wind speed, and Φ_{max} indicates the speed for maximum power output. After performing all the necessary calculations, a Python library called Matplotlib was used in Google Colab to plot graphs based on the wind speed data.

IV. Results and Analysis

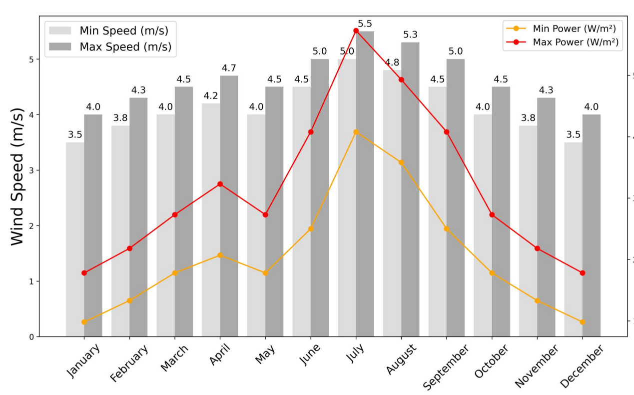

Fig. 1. Rayleigh Forecast for Chattogram (40m)

Figure 1 illustrates the Rayleigh model's predictions for wind speed and power potential at a 40-meter height in Chattogram, highlighting seasonal variations. Wind speeds range from 3.5 to 4.7 m/s, with power generation estimates between 98 to 573 W/m². January experiences the lowest wind speeds, while June and July record the highest, with July showing the strongest winds and maximum power potential. Summer months exhibit the most significant wind activity, whereas wind speeds decline toward year-end, matching January's low levels.

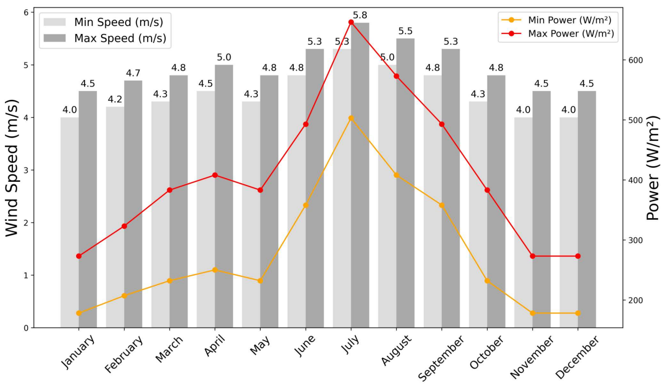

Fig. 2. Rayleigh Forecast for Chattogram (60m)

Figure 2 analyzes wind energy potential in Chattogram at 60 meters using the Rayleigh distribution. Wind speeds are lowest in winter (January-February), increase gradually until April (peaking at 4.5-5.0 m/s), and reach their maximum during summer (June-September), with July showing the highest speeds (5.3-5.8 m/s) and power generation potential. Wind speeds decline in fall (October-December), returning to levels similar to those in winter.

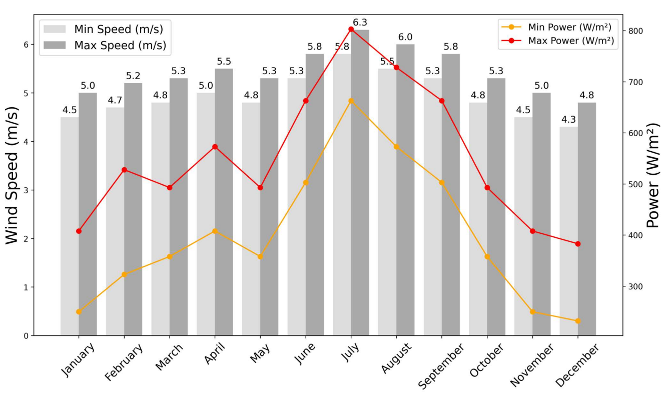

Fig. 3. Rayleigh Forecast for Chattogram (80m)

Figure 3 displays Rayleigh model predictions for wind speed and power potential at an 80-meter height in Chattogram, highlighting seasonal trends. Wind speeds rise from January to April, peaking in April, with power generation ranging from 250 to 573 W/m². May remains similar to March, while June and July exhibit the highest wind speeds and power potential (663–803 W/m²). August sees a slight decline, and September resembles June's conditions. From October to December, wind speeds decrease, returning to levels observed in January.

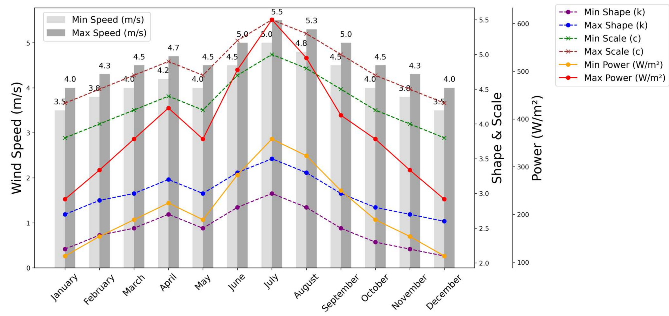

Fig. 4. Weibull Forecast for Chattogram (40m)

Figure 4 illustrates Weibull model predictions for wind speed, form and scale parameters, and power potential at a 40-meter height in Chattogram. From January to April, wind speeds increase, peaking in April, with power generation ranging from 113 to 423 W/m². May reflects March's conditions, while June and July record the highest wind speeds and power potential (283–608 W/m²). August shows a slight decline, and September aligns with June and May. Wind speeds gradually decrease from October to December, resembling January's trends.

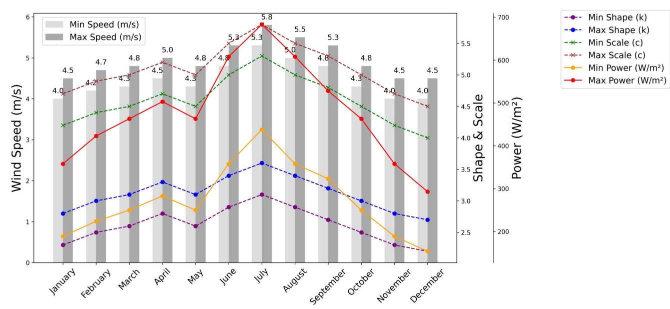

Fig. 5. Weibull Forecast for Chattogram (60m)

Figure 5 presents a full Weibull study of wind energy potential in Chattogram at 60 meters, assessing wind speed fluctuations (including shape and scale factors) and their impact on power output throughout the year. Like the 40 meter data, wind speeds are lowest in winter and rise through spring until peaking in April. Summer has the highest winds and power generating capacity, with July's peak reaching 438-683 W/m². Speeds then diminish in fall, approaching winter levels again.

Figure 6 presents a detailed Weibull analysis of wind energy potential at an 80-meter height in Chattogram, emphasizing wind speeds and Weibull parameters (shape and scale). Consistent with lower altitudes, wind speeds are lowest in winter, rise during spring, and peak in April. Summer records the highest wind speeds and power generation, with July reaching

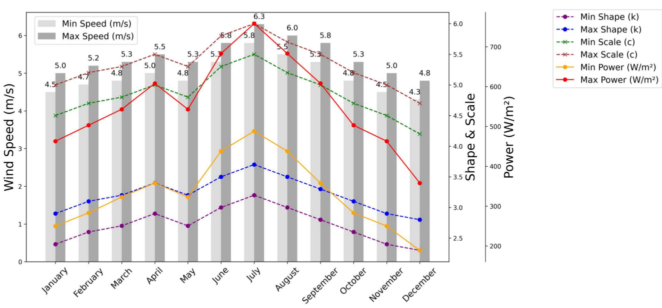

Fig. 6. Weibull Forecast for Chattogram (80m)

a peak potential of 488–758 W/m². Wind speeds decrease in fall, returning to winter levels. This figure highlights the most optimistic scenario for wind energy, demonstrating how wind variability and Weibull parameters impact power generation throughout the year.

This study explores Chattogram's wind energy potential using Rayleigh and Weibull models, emphasizing advanced modeling, economic analysis, and meteorological data. Chattogram's geography makes it suitable for sustainable wind energy, offering benefits like reduced fossil fuel reliance and financial gains. The Weibull model outperforms Rayleigh in capturing wind speed variations, aiding energy planning. Tools like k-means clustering and Weibull-mixture models enhance precision. However, limitations include oversimplified wind behavior, biases from historical data, and exclusion of nonmeteorological factors like land use and community acceptance. Future research should incorporate real-time data, socio-economic considerations, and expand beyond Chattogram. Collaboration among stakeholders is vital for technology transfer, policy development, and capacity building to unlock Bangladesh's broader wind energy potential.

V. Conclusion

The substantial wind energy potential of Chattogram and its contribution to the advancement of sustainable energy are highlighted in this paper. Through statistical models like Weibull and Rayleigh distributions, it analyzes the data and economic evaluations, revealing that Chattogram's geography offers favorable wind conditions for energy generation. It enhances Bangladesh's renewable energy literature by tackling challenges in wind energy assessment and the transition to greener sources, identifying gaps in data collection, socio-economic considerations, and interdisciplinary collaboration. The report advocates for a multidisciplinary approach and stakeholder involvement in developing sustainable energy policies, urging collaboration among policymakers, researchers, industry, and local communities. By leveraging these insights, Bangladesh can enhance energy security, reduce fossil fuel dependences, and contribute to climate change mitigation and sustainable development goals.

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