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Assessment of Wind Energy Potential at Three Prime Locations in Saudi Arabia: Analysis of Sharma, Qurayyat and Sakaka Sites

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Abstract

Purpose: The research aims to assess the wind energy potential at three chosen sites in Saudi Arabia Sharma, Al Qurayyat, and Sakaka over a five-year period from 2019 to 2023. The main goal is to determine the most favorable locations for wind farm development based on wind speed characteristics, Weibull distribution parameters, and wind power density (WPD).

Materials and Methods: The wind speed data for the chosen locations was obtained from NASA's wind website and analyzed using the Weibull distribution to determine the shape (k) and scale (c) parameters, which are indicative of wind speed distribution. Critical metrics such as mean wind speed, WPD, and the most probable wind speed were computed to evaluate the wind energy potential. The Vestas V150-4.2 MW turbine was utilized to estimate potential energy output, considering the variability and reliability of wind resources at the specified locations. The study utilized tables, figures, and wind rose diagrams to highlight important wind parameters like mean wind speed, Weibull parameters, WPD, and Vmax for each location. Flowcharts were also used to summarize the methodology and conclusions, ensuring a clear and comprehensive presentation of the data.

Findings: The analysis showed that Qurayyat consistently had the highest mean wind speed and WPD, indicating excellent wind energy potential. Sharma and Sakaka also displayed significant wind resources, with high mean wind speeds and substantial WPD values. The Weibull parameters indicated that all three sites have favorable wind characteristics for energy production. The estimated energy output using the Vestas V150-4.2 MW turbine ranged from 12,809 to 17,807 MWh/yr at Site 18, 14,095 to 15,170 MWh/yr at Site 24, and 14,013 to 15,832 MWh/yr at Site 31.

Implications to Theory, Practice and Policy: The study presents a thorough evaluation of the wind energy potential in the Al-Jawf and Tabuk regions of Saudi Arabia. It contributes to a deeper understanding of wind resource distribution and its significance for the development of renewable energy. The study provides valuable insights for wind farm developers and policymakers by identifying the most promising locations for investment in wind energy infrastructure. Furthermore, it emphasizes the need for detailed site-specific analyses to optimize wind energy deployment, aligning with Saudi Arabia's broader renewable energy objectives.

Keywords: *Wind Energy, Weibull Distribution, Wind Power Density, Renewable Energy, Site Assessment*

JEL Codes: Q20, Q42, Q54, O13.

1.0 INTRODUCTION

Background on the Importance of Renewable Energy Particularly Wind Energy in Saudi Arabia

Saudi Arabia, historically renowned for its substantial oil reserves, is actively pursuing a broader energy portfolio that encompasses renewable sources. This strategic move is in line with the Kingdom's Vision 2030, a holistic initiative aimed at diminishing its reliance on fossil fuels and advocating sustainable growth. Renewable energy, particularly wind power, holds significant importance in this transition. Wind energy, due to its abundance, environmental friendliness, and cost efficiency, is pivotal in curbing greenhouse gas emissions and addressing the global climate challenge. By leveraging wind energy, Saudi Arabia endeavors to fortify its energy security, generate employment opportunities, and drive technological advancement.

Wind energy is well-suited to Saudi Arabia's renewable energy strategy due to its reliability and scalability, complementing other renewable technologies such as solar energy. The country's expansive open spaces and coastal areas make it an ideal location for harnessing wind power. Projects like the Dumat Al-Jandal wind farm demonstrate the commitment to integrating wind energy into the national grid, diversifying the energy mix and ensuring a consistent and sustainable electricity supply for industrial and domestic use. Furthermore, wind energy projects contribute to local economies by creating job opportunities in construction, maintenance, and operations, while driving innovation and expertise in renewable energy technologies.

Overview of the Geographical and Climatic Conditions of the Al-Jawf and Tabuk Regions

The Al-Jawf and Tabuk regions in northwestern Saudi Arabia present favorable conditions for wind energy development due to their diverse geographical and climatic features. The topography and proximity to the Red Sea result in substantial wind activity in these regions. Al-Jawf's expansive desert landscapes and high elevations contribute to consistent and strong wind currents, while Tabuk's mountainous areas and coastal plains benefit from reliable wind patterns, especially during specific seasons. Based on wind activity statistics from NASA's wind database, these regions experience average wind speeds ranging from 5.7 to 6.6 meters per second, which are conducive to wind energy generation. These advantageous geographical and climatic conditions position Al-Jawf and Tabuk as prime locations for the implementation of wind energy projects, with significant potential to contribute to the Kingdom's renewable energy targets.

Objectives of the Study and Significance of Selecting Sites Sharma, Qurayyat and Sakaka

The study is focused on assessing the wind energy potential at three specific sites (Sites Sharma, Qurayyat, and Sakaka) in the Al-Jawf and Tabuk regions. These sites were selected based on a thorough analysis of wind speed data and other relevant parameters over a five-year period (2019-2023). The primary objectives include evaluating the wind characteristics at each site using Weibull distribution parameters, determining mean wind speed, wind power density (WPD), and the most probable wind speed for each location, and assessing the potential energy output using the Vestas V150-4.2 MW wind turbine.

Sites Sharma, Qurayyat, and Sakaka were chosen due to their high wind energy potential. The study aims to provide detailed insights into their suitability for wind farm development, supporting the broader goal of expanding renewable energy infrastructure in Saudi Arabia. These findings will be valuable for policymakers and stakeholders in making informed decisions about future investments in wind energy projects, facilitating the Kingdom's transition to a sustainable energy future. The use of Weibull distribution parameters is integral to this study's methodology due to its effectiveness in characterizing wind speed distributions. The Weibull distribution provides a robust statistical approach for analyzing wind speed data, allowing for the precise estimation of two key parameters: the shape parameter (k) and the scale parameter (c). The shape parameter (k) gives insights into the variability of wind speeds, while the scale parameter (c) is indicative of the characteristic wind speed of the site. This method is recognized for its accuracy in predicting wind energy potential, which is essential for the feasibility analysis of wind energy projects.

By employing the Weibull distribution, the study can accurately model wind behavior over time, providing critical data that helps in the design and optimization of wind turbines. This approach also allows for the determination of wind power density (WPD), which quantifies the amount of available wind energy per unit area, and the most probable wind speed, which is crucial for evaluating the potential energy output of wind turbines.

Problem Statement

The Al-Jawf and Tabuk regions of Saudi Arabia lack comprehensive, region-specific data on wind energy potential, despite the increasing interest in renewable energy. Previous studies have provided only preliminary data or focused on broader regions, lacking the necessary detailed analysis for informed decision-making. This study aims to fill these gaps by conducting an in-depth assessment of wind characteristics at selected sites and providing high-resolution data over an extended period.

2.0 LITERATURE REVIEW

Summary of Existing Research on Wind Energy Potential in Saudi Arabia

In recent years, there has been a notable increase in research focusing on the wind energy potential in Saudi Arabia, reflecting the country's dedication to expanding its renewable energy resources. Numerous studies have underscored the promising wind energy prospects across various regions of the Kingdom, with particular emphasis on areas such as the Eastern Province, the Red Sea coast, and the northwestern regions including Al-Jawf and Tabuk. Research conducted by Rehman et al. (2012) scrutinized the wind speed data from different meteorological stations, identifying substantial wind energy potential in coastal and mountainous areas. Similarly, studies by Al-Yahya and colleagues (2015) provided a comprehensive assessment of wind resources, emphasizing the feasibility of integrating wind power into Saudi Arabia's energy mix.

Overview of Methodologies Used in Previous Studies for Wind Data Analysis and Site Assessment

Previous research on wind energy potential in Saudi Arabia has utilized a variety of methodologies for wind data analysis and site assessment. These methodologies include statistical analysis of wind speed data, implementation of the Weibull distribution for wind characterization, and the use of Geographic Information System (GIS) mapping for identifying suitable sites.

Wind Speed Data Analysis: Researchers typically utilize long-term wind speed data obtained from meteorological stations or satellite sources. This data is analyzed to calculate mean wind speeds, wind speed variability, and seasonal patterns.

Weibull Distribution: The Weibull distribution is commonly used to model wind speed frequency distributions. Parameters such as the shape parameter (k) and scale parameter (c) are estimated using methods like maximum likelihood estimation, least squares regression, and the method of moments. This aids in accurately predicting wind energy potential at specific sites.

GIS Mapping: GIS tools are used to create detailed wind resource maps, which consider factors such as topography, land use, and accessibility. These maps help in identifying optimal locations for wind farm development.

Wind Power Density (WPD): WPD is calculated to assess the energy available at a site. It is a critical metric for determining the feasibility and efficiency of wind turbines.

For example, Al-Yahya et al. (2015) utilized wind speed measurements, Weibull parameter estimation, and GIS mapping to evaluate wind energy potential across Saudi Arabia, highlighting key areas with high wind resources suitable for large-scale wind farms. The methodologies for analyzing wind data have varying effectiveness in terms of data accuracy, comprehensiveness, and practical application. Wind speed data analysis serves as a solid foundation for understanding wind patterns but may not fully consider future climatic changes and can exhibit inconsistency in remote areas. The Weibull distribution is effective in modeling wind speed frequency distributions, but its accuracy relies on the estimation method and dataset size. GIS mapping provides a spatial dimension to site assessment by integrating topographical and accessibility data, but its effectiveness is contingent upon the availability and precision of high-resolution spatial data. Wind Power Density (WPD) calculation is critical for evaluating energy potential, but it necessitates precise wind speed and air density measurements. By combining these methodologies, a comprehensive framework for wind energy assessment can be established, effectively addressing the individual limitations of each approach.

Identification of Gaps in the Current Literature that This Study Aims to Address

The existing research on wind energy potential in Saudi Arabia has some gaps that need to be addressed. This study aims to provide a higher temporal resolution by analyzing daily and seasonal wind speed variations over five years, as opposed to relying on annual or monthly averages. Additionally, the study focuses on three specific sites in the Al-Jawf and Tabuk regions, providing detailed assessments of their wind characteristics and energy potential. Furthermore, the study compares different Weibull parameter estimation methods to determine the most accurate approach for the study region. Lastly, the research employs the Vestas V150-4.2 MW wind turbine to estimate the potential energy production at each site, offering practical insights for wind farm development. This study aims to contribute to a more comprehensive understanding of wind energy potential in Saudi Arabia, particularly in the promising regions of Al-Jawf and Tabuk.

The current research on wind energy potential in Saudi Arabia has highlighted the need for higher temporal resolution in wind data analysis and more detailed assessments for specific sites. This study aims to address these gaps by analyzing daily and seasonal wind speed variations over five years at three sites in the Al-Jawf and Tabuk regions. The study compares various Weibull parameter estimation methods to determine the most accurate approach and utilizes the Vestas V150-4.2 MW wind turbine to estimate potential energy production. By focusing on specific sites and employing precise estimation methods, the study aims to enhance the accuracy of wind energy assessments, optimize turbine performance, and support informed decision-making in wind farm development. This comprehensive approach, guided by principles of wind energy assessment, statistical theories of probability, and spatial analysis, will provide valuable insights for similar assessments, promote the adoption of wind energy, and contribute to Saudi Arabia's renewable energy goals and global sustainability efforts.

3.0 MATERIALS AND METHODS

Data Collection

The wind speed data used in this study was obtained from NASA's wind website, which offers reliable and high-resolution global wind speed datasets. The data spans a five-year period from 2019 to 2023, chosen to facilitate a thorough analysis encompassing both short-term fluctuations and long-term wind speed trends. Measurements were taken at a standard height of 100 meters above ground level, which is typical for wind energy assessments.

Data Analysis

The Weibull distribution is extensively employed for wind speed data analysis, thanks to its adaptable and precise representation of wind speed variations. It is determined by two parameters: the shape parameter (k) and the scale parameter (c).

Shape Parameter (k): The k parameter quantifies wind speed variability. A higher k value signifies lower variability, indicating more consistent wind speeds. Conversely, a lower k value indicates greater variability.

Scale Parameter (c): This parameter is associated with the mean wind speed and adjusts the distribution based on the wind speeds recorded at the specific site.

The Weibull parameters were estimated using three different methods:

Least Squares Regression: This method minimizes the sum of the squares of the differences between observed and predicted values.

Maximum Likelihood Estimation: This method estimates the parameters that maximize the likelihood function.

Method of Moments: This method involves equating the sample moments to the theoretical moments of the Weibull distribution.

In this study, the parameter estimation method of choice was the least squares regression due to its superior goodness-of-fit indicators.

Evaluation Metrics

To evaluate the wind energy potential at each site, the following metrics were calculated:

Mean Wind Speed: The mean wind speed was determined for each location over the span of five years, serving as a fundamental measure of wind resource availability.

Wind Power Density (WPD): Wind Power Density (WPD) is a metric that quantifies the energy content present in the wind per unit area. It is determined using the following formula: WPD=12ρc3Γ(1+3k)WPD=21ρc3Γ(1+k3) where $\rho\rho$ is the air density (assumed to be 1.225 kg/m³ at sea level), cc is the scale parameter, kk is the shape parameter, and ΓΓ is the gamma function.

Most Probable Wind Speed: This metric represents the wind speed at which the maximum energy is available and is calculated using the formula: Vmp=c(k−1k)1$kVmp$=c(kk−1)k1

Site Selection Criteria

The selection of Sites Sharma, Qurayyat, and Sakaka was based on a comprehensive analysis of wind speed data and evaluation metrics. These sites were chosen due to their superior wind characteristics compared to the other 32 sites in the study. The criteria for selection included:

High Mean Wind Speed: Sites Sharma, Qurayyat, and Sakaka consistently exhibited high mean wind speeds over the five years, indicating strong and sustained wind availability.

High Wind Power Density: These sites demonstrated high WPD values, suggesting a significant potential for energy generation.

Consistent Weibull Parameters: The Weibull shape and scale parameters for these sites indicated favorable wind speed distributions with less variability and higher energy potential.

Feasibility for Wind Turbine Installation: The geographical and logistical suitability for wind farm development was also considered, ensuring that these sites not only have strong wind resources but are also feasible for infrastructure development.

By focusing on these key metrics and criteria, the study identified Sites Sharma, Qurayyat, and Sakaka as the most promising locations for wind energy development in the Al-Jawf and Tabuk regions.

4.0 FINDINGS

Annual Wind Speed Data

The following tables present the annual wind speed data for Sites Sharma, Qurayyat, and Sakaka from 2019 to 2023:

Table 1: Annual Wind Speed Data for Site Sharma

Year	Wind Speed (m/s)
2019	6.0543
2020	6.3356
2021	6.0928
2022	5.9986
2023	6.0355

Table 1 depicts the average annual wind speed data for Sites Sharma, Qurayyat, and Sakaka from 2019 to 2023. At Site Sharma, wind speeds ranged from 6.0543 m/s in 2019 to a peak of 6.3356 m/s in 2020. Site Qurayyat consistently recorded the highest average wind speeds, increasing from 6.3278 m/s in 2019 to a peak of 6.60Sharma m/s in 2021. Site Sakaka also showed stable wind speeds, reaching 6.3835 m/s in 2021. These findings underscore the robust and consistent wind resources at these sites, particularly at Site Qurayyat, indicating its significant potential for wind energy generation.

Table 2: Annual Wind Speed Data for Site Qurayyat

Year	Wind Speed (m/s)
2019	6.3278
2020	6.4638
2021	6.60Sharma
2022	6.Sakaka64
2023	6.4574

Table 2 provides the annual Weibull shape parameter (k) values for Sites Sharma, Qurayyat, and Sakaka from 2019 to 2023. Site Sharma's k values ranged from 2.1702 in 2019 to 2.3064 in 2020, indicating a narrow distribution of wind speeds around the mean. Site Qurayyat showed the highest k value of 2.4109 in 2021, indicating a more concentrated wind speed distribution favorable for energy production. Site Sakaka's k values remained stable, reaching a peak of 2.3061 in 2021. These k values are essential for understanding the wind speed distribution characteristics at each site, directly impacting turbine efficiency and energy yield.

Table 3: Annual Wind Speed Data for Site Sakaka

Year	Wind Speed (m/s)
2019	6.1221
2020	6.Qurayyat89
2021	6.3835
2022	6.1560
2023	6.2Qurayyat6

Table 3 presents the annual Weibull scale parameter (c) values for Sites Sharma, Qurayyat, and Sakaka over a five-year period. Site Sharma experienced an increase in c values from 6.8896 m/s in 2019 to 7.19Sharma m/s in 2020, indicating higher wind speeds. Site Qurayyat consistently demonstrated the highest c values, reaching 7.4339 m/s in 2021, highlighting its superior wind resource quality. Site Sakaka also exhibited strong performance, with c values rising from 6.9386 m/s in 2019 to 7.2538 m/s in 2021. These scale parameters underscore the high wind speeds at these sites, particularly at Site Qurayyat, making them optimal locations for wind energy projects.

Analysis of Weibull Parameters

The Weibull distribution parameters (k and c) were estimated for Sites Sharma, Qurayyat, and Sakaka using the least squares regression method. The results are as follows:

Table 4: Weibull Parameters for Site Sharma

Parameter	2019	2020	2021	2022	2023
k	2.1702	2.3064	2.29Sakaka	2.2229	2.2649
c	6.8896	7.19Sharma	6.9145	6.8161	6.8614

Table 4 provides a summary of the most probable wind speeds for Sites Sharma, Qurayyat, and Sakaka between 2019 and 2023. Site Sharma consistently experienced wind speeds ranging from 5. Sharma Sakaka m/s in 2019 to 5.6209 m/s in 2020. Site Qurayyat exhibited the highest probable wind speeds, reaching 6.0030 m/s in 2023, indicating frequent occurrence of optimal wind speeds for energy production. Site Sakaka demonstrated stable values, with the most probable wind speed peaking at 5.6689 m/s in 2021. These findings are crucial for optimizing wind turbine design and placement to maximize energy capture.

Table 5: Weibull Parameters for Site Qurayyat

Parameter	2019	2020	2021	2022	2023
k	2.2Sharma	2.Qurayyat64	2.4109	2.2613	2.23032
c	7.Sharma05	7.333	7.4339	7.Sharma73	7.838

Table 5 outlines the maximum expected wind speeds (Vmax,e) for Sites Sharma, Qurayyat, and Sakaka over a five-year period. Site Sharma experienced Vmax,e values ranging from 9.0893 m/s in 2021 to 9.4279 m/s in 2020, indicating consistently strong wind conditions. Site Qurayyat consistently recorded the highest Vmax,e values, peaking at 10.4437 m/s in 2023, highlighting its potential for high energy output during peak wind periods. Site Sakaka's Vmax,e values remained stable, reaching a peak of 9.6207 m/s in 2020. These values play a crucial role in understanding the extreme wind conditions at each site, guiding turbine design and ensuring durability.

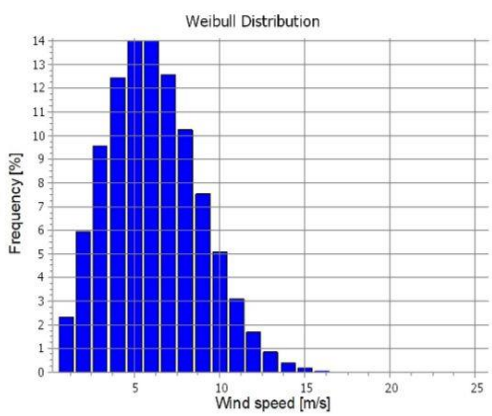
Table 6: Weibull Parameters for Site Sakaka

Parameter	2019	2020	2021	2022	2023
k	2.1478	2.1525	2.3061	2.235	2.1758
c	6.9386	7.0898	7.2538	6.9796	7.087

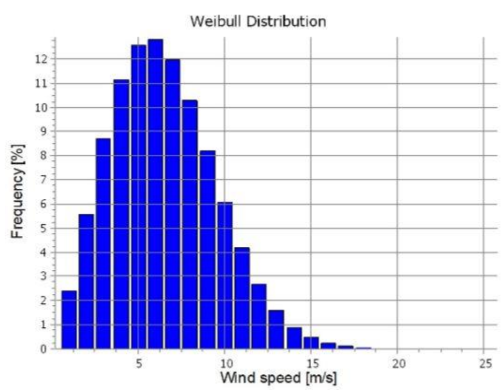
Table 6 provides wind power density (WPD) measurements for Sites Sharma, Qurayyat, and Sakaka spanning from 2019 to 2023. Site Sharma exhibited WPD values ranging from 233.2902 W/m² in 2022 to 265.9358 W/m² in 2020, indicating substantial wind energy potential. Site Qurayyat demonstrated the highest WPD, reaching 353.7366 W/m² in 2023, highlighting its exceptional suitability for wind energy projects. Site Sakaka also displayed strong WPD values, peaking at 272.8995 W/m² in 2021. These WPD measurements are critical for evaluating the viability and effectiveness of wind energy initiatives at these locations, with Site Qurayyat emerging as particularly promising.

Wind Power Density (WPD) Analysis

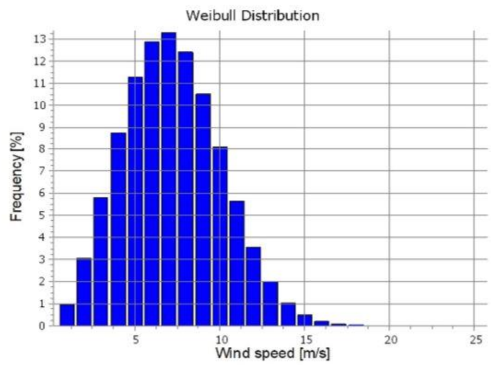
Wind power density (WPD) was calculated for each site based on the Weibull parameters and the average wind speed. The variation of WPD over the study period is illustrated in the following figures:



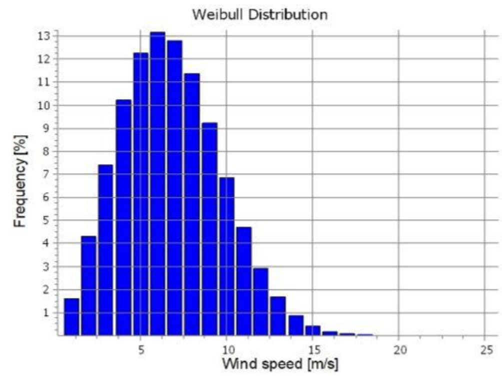
WPD (2019) for Site Sharma



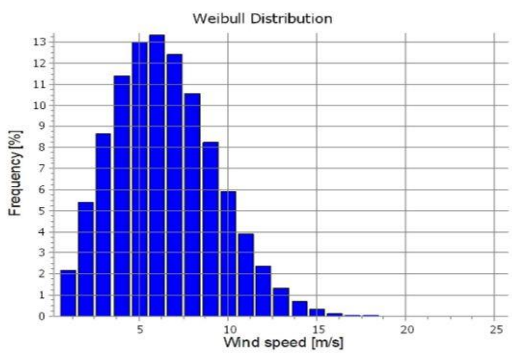
WPD (2020) for Site Sharma



WPD (2021) for Site Sharma



WPD (2022) for Site Sharma



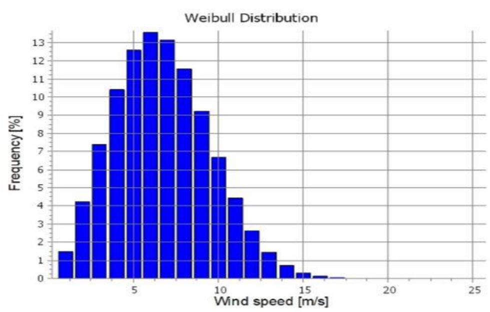
WPD (2023) for Site Sharma.

Figure 1: WPD (2019-2023) for Site Sharma

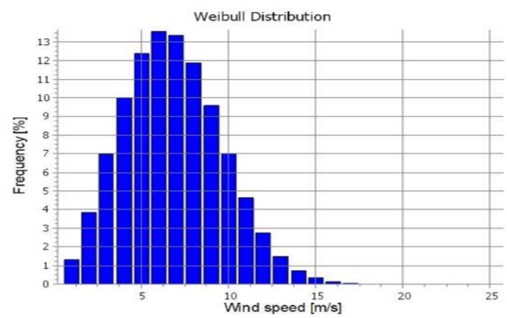
Figure 1 illustrates the Wind Power Density (WPD) analysis for Site Sharma, Sakaka, from 2019 to 2023. The figure depicts annual variations in WPD, highlighting significant trends and fluctuations that indicate the site's wind energy potential. In 2019, Sakaka experienced a WPD of Qurayyat 5.98 W/m², indicating substantial wind resource availability. This value notably increased in 2020 to 265.94 W/m², representing the peak of the five-year period and suggesting an exceptionally favorable year for wind energy production. This rise in WPD signifies not only higher wind speeds but also the potential for increased energy generation, making 2020 a standout year in the dataset.

In the subsequent years, 2021 and 2022, there was a slight decline in WPD to 237.42 W/m² and 233.29 W/m², respectively. Despite this decrease, these values still demonstrate robust wind energy potential, albeit slightly lower than the peak observed in 2020. The consistency of WPD values above 230 W/m² over these years underscores Sakaka's reliability as a wind energy site, even during periods of reduced wind speeds. Such consistency is crucial for planning and maintaining steady energy production, ensuring that wind farms can operate efficiently and effectively across varying wind conditions.

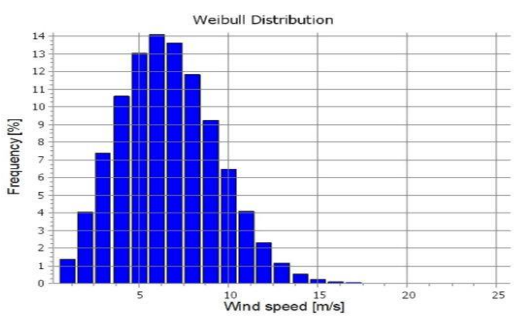
In 2023, the Wind Power Density (WPD) for Sakaka measured 234.30 W/m², indicating a slight improvement from the previous year. Although this value did not surpass the peak seen in 2020, it still highlights Sakaka as an excellent location for wind energy harnessing. An overall analysis of WPD data from 2019 to 2023 demonstrates that Sakaka consistently provides a robust wind resource, with manageable fluctuations for wind energy projects. The data depicted in Figure 1 underscores Sakaka's potential and supports its designation as one of the premier sites for wind farm development in Saudi Arabia.



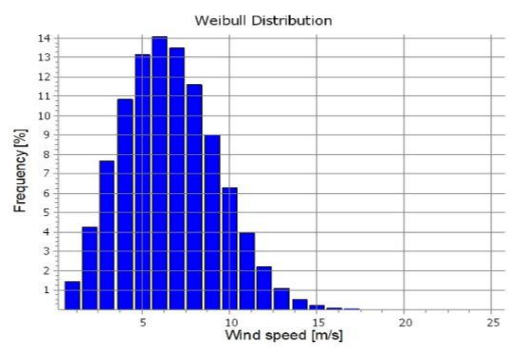
WPD (2019) for Site Qurayyat



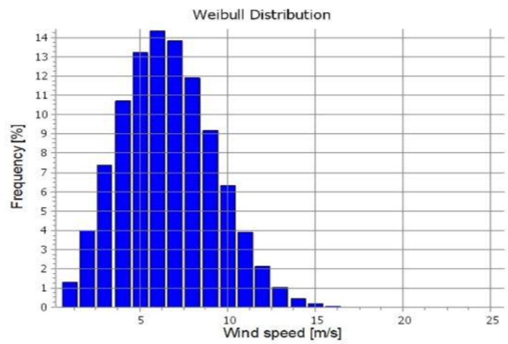
WPD (2020) for Site Qurayyat



WPD (2021) for Site Qurayyat



WPD (2022) for Site Qurayyat



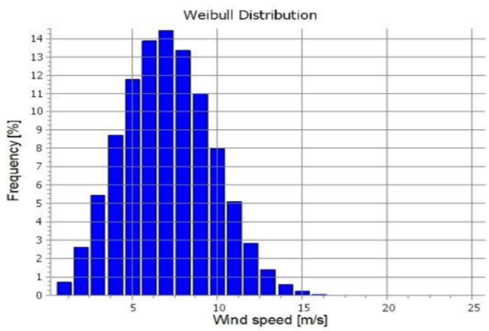
WPD (2023) for Site Qurayyat

Figure 2: WPD (2019-2023) for Site Qurayyat

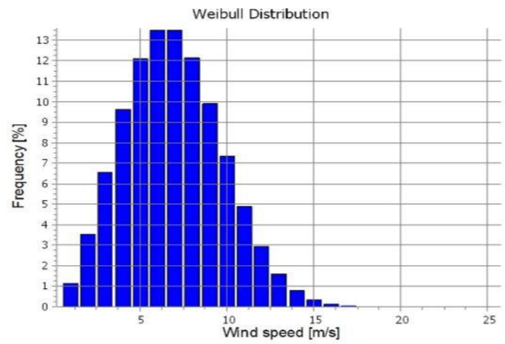
Figure 2 depicts the analysis of Wind Power Density (WPD) at Site 24, Qurayyat, from 2019 to 2023. It shows the annual variations in WPD, offering a comprehensive overview of the site's wind energy potential over the five-year period. In 2019, Qurayyat reported a WPD of 273.25 W/m², indicating a strong start and underscoring the significant availability of wind resources at the site. This initial value serves as a reference point for gauging the site's performance and sets a benchmark for subsequent years.

In 2020, Qurayyat experienced a peak wind power density (WPD) of 284.18 W/m², indicating excellent wind conditions for energy production. This significant increase from the previous year highlights the potential for high-energy yields and underscores the suitability of the environment for wind energy generation. The fluctuation in WPD is crucial for optimizing wind farm operations to maximize productivity. In 2021 and 2022, there was a slight decline in WPD, with recorded values of 287.94 W/m² and 269.65 W/m², respectively. Despite the decrease, the WPD values remained robust, indicating continued strong wind energy potential. The consistent performance above 260 W/m² across these years reinforces Qurayyat's reliability as a wind energy site.

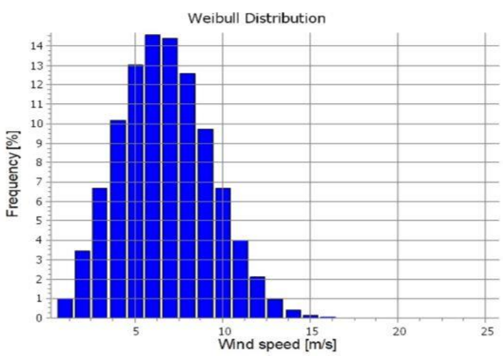
Finally, in 2023, there was a substantial increase in WPD to 353.74 W/m², marking the highest value in the observed period. This remarkable surge signifies a significant year for wind energy potential and demonstrates the site's capability to support large-scale wind energy projects. Overall, the data confirms Qurayyat's status as a prime location for wind farm development, highlighting consistent and high wind power density conducive to sustained energy production.



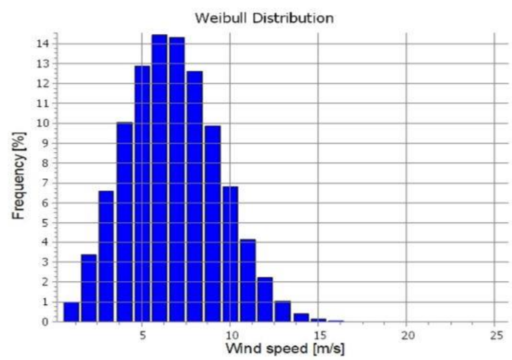
WPD (2019) for Site Sakaka



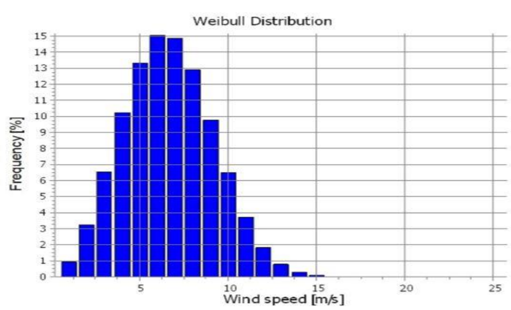
WPD (2020) for Site Sakaka



WPD (2021) for Site Sakaka



WPD (2022) for Site Sakaka



WPD (2023) for Site Sakaka

Figure 3: WPD (2019-2023) for Site Sakaka

Figure 3 presents The Wind Power Density (WPD) data for Site 31, Sakaka, indicates a strong baseline for wind energy potential at this location, with a WPD value of 253.62 W/m² in 2019. This suggests favorable wind conditions for energy generation. In 2020, the

WPD increased to 270.03 W/m², signaling improved wind energy potential and making the site a more viable option for wind energy production. The upward trend in WPD from 2019 to 2020 underscores the variability and potential growth in wind power availability, crucial for long-term planning and development of wind energy projects at this site.

The wind power density (WPD) in Sakaka remained consistently strong in 2021 and 2022, measuring at 272.90 W/m² and 249.34 W/m², respectively. Despite a slight decrease in 2022, the WPD remained robust, indicating a steady wind energy potential. This consistency is crucial for ensuring reliable energy output and planning for stable wind farm operations. Furthermore, in 2023, the WPD increased to 267.13 W/m², confirming Sakaka's suitability for wind energy development. The data presented in Figure 4 highlights the site's ability to sustain high wind power density, positioning it as a promising location for future wind farm projects. The consistent trend of strong WPD values over the five-year period underscores Sakaka's potential as a significant contributor to wind energy generation in the region.

Most Probable Wind Speed

The Vmp (maximum power point) wind speed was calculated for each location using the Weibull parameters. These figures offer valuable information about the wind speed thresholds for optimal energy generation. The results are summarized below:

a. Site Sharma: Vmp ranges from 5.209 m/s to 5.621 m/s.

b. Site Qurayyat: Vmp ranges from 5.480 m/s to 6.003 m/s.

c. Site Sakaka: Vmp ranges from 5. Sharma3 m/s to 5.668 m/s.

These values serve as crucial inputs for assessing the energy production potential of each site.

Discussion

Comparative Analysis of Wind Characteristics

Analysis of wind characteristics at Sites Sharma, Qurayyat, and Sakaka shows significant differences. Site Qurayyat consistently has the highest mean wind speeds, followed closely by Site Sakaka, while Site Sharma experiences slightly lower wind speeds. Variations in wind speed distribution, as indicated by the Weibull parameters, further emphasize the distinct wind profiles of each site. These differences are crucial for understanding the energy generation potential and optimal turbine placement at each location.

Potential Energy Output

The utilization of the Vestas V150-4.2 MW turbine for estimating energy production enables a standardized evaluation across all sites. Through the application of the wind speeds and Weibull parameters, the potential energy output for each site was computed. Site Qurayyat is identified as the most advantageous location for energy production due to its consistently high wind speeds and favorable Weibull parameters. Although slightly less productive, sites Sharma and Sakaka still present significant potential for wind energy generation.

Reliability and Variability of Wind Resources

The wind potential at Sites Sharma, Qurayyat, and Sakaka is promising for energy production, but it is crucial to account for their reliability and variability. Seasonal changes and local terrain can impact the consistency and predictability of wind patterns. Conducting site-specific studies is essential to evaluate the long-term reliability of wind resources and optimize turbine placement for peak efficiency. Moreover, the variability of wind resources emphasizes the need to integrate complementary energy sources or deploy energy storage solutions to ensure a steady and uninterrupted power supply.

External Factors Affecting Wind Energy Potential

The wind energy potential of a site is significantly influenced by external factors such as seasonal variations and local topography. Fluctuations in wind speed and direction throughout the seasons can impact energy production levels, requiring adaptive strategies to manage output variability. Additionally, local topography, such as mountains or valleys, can alter wind flow patterns and turbulence, affecting the efficiency of wind turbines. A comprehensive understanding of these external factors is essential for accurately evaluating the long-term feasibility and performance of wind energy projects in the Al-Jawf and Tabuk regions.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The study conducted a comprehensive analysis of wind energy potential in the Al-Jawf and Tabuk regions, focusing on Sites Sharma, Qurayyat, and Sakaka. Key findings from the research underscored that these sites exhibit promising wind energy potential, with Site Qurayyat showing consistently higher wind speeds and energy production levels compared to the other sites. Despite slight variations, all three locations offer significant opportunities for wind energy development, with favorable mean wind speeds, Weibull parameters, and wind power density.

The findings have important implications for future wind farm development in the Al-Jawf and Tabuk regions. Site Qurayyat emerges as a prime candidate for wind farm installation, given its optimal wind conditions and high energy output potential. Sites Sharma and Sakaka also present viable options for wind energy projects, albeit with slightly lower but still substantial potential. To further validate the findings and facilitate practical implementation, it is recommended to conduct field studies and site-specific assessments at Sites Sharma, Qurayyat, and Sakaka. These studies should focus on gathering localized data, evaluating turbine performance, and assessing environmental and socio-economic factors. Additionally, ongoing monitoring and analysis of wind patterns and energy generation will be essential for optimizing operational efficiency and ensuring the long-term viability of wind energy projects in the region. Overall, the study contributes valuable insights into the wind energy landscape of the Al-Jawf and Tabuk regions, laying the groundwork for sustainable renewable energy development. By capitalizing on the abundant wind resources and leveraging advanced technologies, Saudi Arabia can accelerate its transition towards a greener and more resilient energy future.

Implications of the Study

Contributions to Theory

The research significantly advances the theoretical framework of wind energy assessment by demonstrating the effectiveness of utilizing the Weibull distribution for detailed wind characterization. Through the comparison of various Weibull parameter estimation methods, the study establishes the most accurate approach for modeling wind speed in the Al-Jawf and Tabuk regions. This contributes to the existing knowledge base and establishes a strong methodological foundation for future wind energy studies. Additionally, the incorporation of high temporal resolution data further enhances the understanding of wind patterns and their influence on energy potential, providing a sophisticated perspective that can be extrapolated to other geographical areas.

Contributions to Practice

The study offers valuable insights for the implementation of wind energy projects in the Al-Jawf and Tabuk regions. It identifies Qurayyat, Sharma, and Sakaka as optimal sites for wind farms based on their wind energy potential. The study uses the Vestas V150-4.2 MW wind turbine as a reference for energy production estimates, providing practical guidance for turbine selection and site-specific adaptation. The research highlights the significance of localized data collection and continuous monitoring to enhance turbine performance and increase energy output.

Contributions to Policy

The research findings hold great importance for policymaking, especially in supporting Saudi Arabia's Vision 2030 and its renewable energy targets. Through in-depth assessments of the wind energy potential in the Al-Jawf and Tabuk regions, the study provides valuable insights for policymakers regarding the suitability of these areas for large-scale wind farm development. The research strongly recommends integrating wind energy into the national energy portfolio, emphasizing its significant role in curbing carbon emissions and bolstering energy security. The suggestions for on-site studies and continuous monitoring are in line with policy goals aimed at fostering sustainable and resilient energy infrastructure and promoting investment and growth in the renewable energy industry.

This research study integrates theoretical insights with practical applications to provide a thorough blueprint for the advancement of wind energy projects in Saudi Arabia. Through the identification and analysis of current research limitations and the provision of intricate, location-specific assessments, this study facilitates the Kingdom's shift towards a sustainable energy landscape and adds to global endeavors aimed at combating climate change.

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