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Preliminary Wind Resource and Indicative Techno-Economic Assessment of Mountainous Terrain: A Case Study of the Jabal Al Gharbi Region, Libya

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تقييم أولي لموارد الرياح وتقييم تقني-اقتصادي إرشادي للمناطق الجبلية: دراسة حالة لمنطقة جبل الغربي، ليبيا

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Abstract

Wind energy plays a crucial role in the global transition toward sustainable energy systems due to its ability to reduce reliance on fossil fuels and mitigate greenhouse gas emissions. Despite extensive research on wind resource assessment, mountainous and complex-terrain regions remain relatively underexplored compared to coastal and flat areas. This is mainly attributed to the complexity of wind flow behavior and the higher uncertainty associated with measurements and modeling in such environments. This study presents a preliminary assessment of wind energy resources in the Jabal Al Gharbi region of western Libya, with a particular emphasis on evaluating the suitability of mountainous terrain for wind energy system design from both technical and economic perspectives.

The assessment is based on monthly mean wind speed data recorded at the Yefren meteorological station over the period 2011-2020. Statistical analyses were conducted to examine seasonal and inter-annual wind speed variability. The probabilistic characteristics of wind speed were modeled using the Wei-bull distribution, with a Rayleigh approximation adopted due to the limited temporal resolution of the available data. Wind power density was estimated accordingly, and the power law was applied to extrapolate wind speed to different turbine hub heights.

The results indicate that the overall mean wind speed at the reference height is approximately 4.35 m/s, corresponding to a wind power density of about 96 W/m², which reflects a low-to-moderate wind resource near the surface. However, wind speed extrapolation reveals a pronounced increase with height, with mean wind speeds exceeding 6.8 m/s at a hub height of 100 m. This highlights the significant influence of vertical wind shear and orographic effects in mountainous terrain, which can substantially enhance wind energy potential at elevated levels. A preliminary and indicative techno-economic evaluation was conducted for a representative 2 MW onshore wind turbine installed at a 100 m hub height using monthly averaged wind speed data provided by the Libyan National Meteorological Center (Yefren meteorological station)
.Based on conservative assumptions for annual energy production, the levelized cost of energy was estimated to range between 0.34 and 0.49 LYD/kWh. The findings suggest that, despite moderate near-surface wind speeds, mountainous regions such as Jabal Al Gharbi can offer technically and economically viable conditions for wind energy development when appropriate design considerations are applied. The study provides a foundation for future investigations incorporating high-resolution measurements and advanced modeling to reduce uncertainty in complex terrain.

Keywords: Wind energy, Wind resource assessment, Mountainous terrain, Weibull distribution, Wind power density, Techno-economic analysis, Jabal Al Gharbi, Libya.

الملخص

تُعدّ طاقة الرياح من أبرز مصادر الطاقة المتجددة لما لها من دور مهم في تقليل الاعتماد على الوقود الأحفوري وخفض الانبعاثات الكربونية. وعلى الرغم من التوسع الكبير في دراسات تقييم موارد الرياح، لا تزال المناطق الجبلية والتضاريس المعقدة أقل دراسة مقارنة بالمناطق الساحلية والمسطحة، وذلك بسبب تعقيد السلوك الهوائي وارتفاع مستويات عدم اليقين في القياسات والنمذجة. تهدف هذه الدراسة إلى إجراء تقييم أولي لموارد طاقة الرياح في منطقة الجبل الغربي بليبيا، مع التركيز على مدى ملاءمة التضاريس الجبلية لتصميم منظومات طاقة الرياح من الناحية التقنية والاقتصادية.
اعتمدت الدراسة على بيانات متوسطات سرعة الرياح الشهرية المسجلة في محطة يفرن للأرصاد الجوية خلال الفترة من 2011 إلى 2020. تم تحليل البيانات إحصائيًا لدراسة التغيرات الموسمية والسنوية، كما استُخدم توزيع ويبول مع اعتماد تقريب رايلي لتمثيل السلوك الاحتمالي لسرعة الرياح وتقدير كثافة طاقة الرياح. إضافة إلى ذلك، استُخدم قانون القدرة لتمديد سرعة الرياح مع الارتفاع وتقدير سرعات الرياح عند ارتفاعات محاور توربينات مختلفة.
أظهرت النتائج أن متوسط سرعة الرياح الكلي عند الارتفاع المرجعي يبلغ نحو 4.35 م/ث، مع كثافة طاقة رياح تُقدّر بحوالي 96 واط/م²، ما يشير إلى مورد ريحي منخفض إلى متوسط عند السطح. إلا أن تمديد سرعة الرياح مع الارتفاع كشف عن زيادة ملحوظة في سرعة الرياح، حيث تجاوزت 6.8 م/ث عند ارتفاع 100 م، مما يعكس التأثير الإيجابي للقص الرأسي والتضاريس الجبلية.
كما تم إجراء تقييم تقني اقتصادي أولي وإرشادي لتوربين رياح بري نموذجي بقدرة 2 ميجاواط مثبت على ارتفاع محور يبلغ 100 متر بناءً على بيانات متوسط سرعة الرياح الشهرية، والتي تم الحصول عليها من المركز الوطني للأرصاد الجوية الليبي (محطة يفرين). حيث قُدرت التكلفة المستوية للطاقة بنطاق يتراوح بين 0.34 و0.49 دينار ليبي/ك.و.س. تشير النتائج إلى أن منطقة الجبل الغربي قد تمثل خيارًا مناسبًا

لتطبيق مشاريع طاقة رياح متوسطة الحجم، شريطة اختيار ارتفاعات محاور مناسبة وإجراء دراسات ميدانية أكثر تفصيلًا مستقبلًا.

الكلمات المفتاحية: طاقة الرياح، تقييم موارد الرياح، التضاريس الجبلية، توزيع ويبل (Weibull Distribution)، كثافة طاقة الرياح، التحليل الفني والاقتصادي، جبل الغربي، ليبيا..

Introduction:

Wind energy has become one of the most rapidly growing renewable energy technologies worldwide due to its technical maturity,
declining installation costs, and significant contribution to reducing greenhouse gas emissions and dependence on fossil fuels [1,2]. As part of the global transition toward sustainable energy systems, accurate assessment of wind resources is essential to ensure the technical feasibility and economic viability of wind energy projects [3].

Wind resource assessment typically involves statistical analysis of wind speed data to characterize temporal variability and estimate key indicators such as wind power density and annual energy production. Among various probabilistic approaches, the Weibull distribution remains the most widely adopted model due to its flexibility and ability to represent wind speed behavior across different climatic conditions [4,5]. However, the accuracy of such assessments strongly depends on data availability, temporal resolution, and site characteristics.

Most existing wind energy studies have focused on coastal and flat regions, where wind flow patterns are relatively uniform and easier to measure and model [6]. In contrast, mountainous and complex-terrain regions remain significantly underrepresented in the literature. This is primarily due to the complex interaction between wind flow and topography, which results in strong spatial variability, enhanced turbulence intensity, and pronounced vertical wind shear [7,8]. These factors introduce additional uncertainty in wind measurements, statistical modeling, and energy yield estimation.

Recent studies have emphasized that mountainous terrain can exhibit favorable wind conditions at elevated locations due to orographic acceleration and increased exposure to prevailing winds [9]. Nevertheless, these potential advantages are often accompanied by technical challenges related to turbine loading, fatigue, and micrositing complexity [10]. As a result, the suitability of mountainous regions for wind energy system design requires careful evaluation that integrates both wind resource characteristics and techno-economic considerations.

In Libya, wind energy research has largely concentrated on coastal are as, while inland mountainous regions such as the Jabal-Al-Gharbi remain insufficiently studied. Despite the region’s elevated topography and strategic geographic location, limited scientific work has addressed its wind energy potential using systematic statistical and economic analyses. This lack of localized studies represents a clear research gap, particularly in the context of assessing whether mountainous terrain can support technically and economically viable wind energy systems.

Therefore, this study aims to provide a preliminary wind resource and techno-economic assessment of the Jabal Al Gharbi region based on available meteorological data. The objectives are to characterize wind speed behavior, evaluate wind energy potential at different hub heights, and assess the economic feasibility of wind energy deployment in mountainous terrain. The findings of this research are intended to support future detailed investigations and contribute to informed decision-making regarding wind energy development in complex-terrain regions of Libya.

Study Area And Wind Data

The present study focuses on the Jabal Al Gharbi region, located in western Libya, which is characterized by elevated terrain and complex topographical features. The region forms part of a mountainous plateau with elevations exceeding several hundred meters above sea level and is influenced by both continental and Mediterranean climatic conditions. Such geographic and climatic characteristics make the Jabal Al Gharbi region a representative case for investigating wind energy potential in mountainous and complex-terrain environments [6,7].

Wind speed data used in this study were obtained from the Yefren meteorological station, which is considered representative of the central part of the Jabal Al Gharbi region. The station provides long-term wind observations that are suitable for preliminary wind resource assessment in areas where high-resolution measurements are not readily available. The dataset consists of monthly mean wind speed records covering a ten-year period from 2011 to 2020.

Table 1. Long-term monthly mean wind speed at Yefren meteorological station (2011–2020)

Month	Mean Wind Speed (knots)	Mean Wind Speed (m/s)
January	9.01	4.63
February	8.61	4.42
March	9.35	4.81
April	9.18	4.72
May	8.87	4.56
June	8.49	4.37
July	7.79	4.01
August	7.62	3.92
September	8.01	4.12
October	8.03	4.13
November	8.50	4.37
December	8.09	4.16

The presented values represent long-term monthly mean wind speeds derived from meteorological records provided by the Libyan National Meteorological Center (Yefren station) for the period 2011–2020. Incomplete records were excluded from averaging calculations where necessary.

The wind speed measurements were originally recorded in knots and subsequently converted to meters per second (m/s) to ensure consistency with international wind energy assessment standards. The use of monthly mean wind speed data allows for the evaluation of long-term seasonal and interannual wind variability; however, it does not capture short-term fluctuations or extreme wind events. This limitation is commonly encountered in preliminary assessments and has been widely acknowledged in recent wind energy studies conducted in data-scarce regions [8 , 9].

Despite these limitations, several studies have demonstrated that monthly averaged wind speed data can provide a reliable first-order estimation of wind resource characteristics when combined with appropriate statistical modeling techniques [11]. In particular, such datasets are useful for identifying general wind regimes, estimating wind power density, and assessing the potential suitability of a site for further detailed investigation.

The complex terrain of the Jabal Al Gharbi region is expected to significantly influence local wind behavior through orographic acceleration, enhanced vertical wind shear, and increased turbulence intensity. These effects can result in substantial spatial variability of wind conditions over relatively short distances, which poses challenges for wind resource assessment but also offers opportunities for enhanced wind speeds at elevated locations [11,8]. Consequently, the analysis presented in this study should be regarded as a preliminary step toward a more comprehensive wind energy evaluation based on site-specific measurements and advanced numerical modeling.

Methodology

The methodology adopted in this study aims to provide a preliminary wind resource and techno-economic assessment suitable for data-limited and complex -terrain environments. The analysis framework consists of four main steps: statistical analysis of wind speed data, probabilistic modeling using the Weibull distribution, estimation of wind power density, and extrapolation of wind speed to different turbine hub heights.

Statistical Analysis of Wind Speed

Monthly mean wind speed data were statistically analyzed to characterize the temporal behavior of wind conditions in the Jabal Al Gharbi region. Seasonal variability was assessed by computing long-term monthly averages, while interannual variability was evaluated using annual mean wind speed values derived from the available monthly data.

Due to the use of monthly averaged wind speed records, the analysis focuses on long-term wind characteristics rather than short-term fluctuations. This approach is widely adopted in preliminary wind resource assessments, particularly in regions where high-resolution wind measurements are unavailable [3,6].

Wind Speed Probability Distribution

The probabilistic behavior of wind speed was modeled using the Weibull distribution, which is commonly employed in wind energy studies due to its flexibility and suitability for representing a wide range of wind regimes [4]. The Weibull probability density function (PDF) is expressed as:

$$f(v)=\frac{k}{c}\left(\frac{v}{c}\right)^{k-1}\exp\left[-\left(\frac{v}{c}\right)^{k}\right] \qquad \text{……………….(1)}$$

where v is the wind speed (m/s), k is the dimensionless shape parameter, and c is the scale parameter (m/s).

Given the limited temporal resolution of the dataset, a Rayleigh distribution was adopted as a special case of the Weibull distribution by assuming a fixed shape parameter k=2. This approximation has been shown to provide reasonable estimates the Rayleigh approximation (k=2) was adopted due to the limited temporal resolution of the available wind speed data and is intended to provide a preliminary first-order estimation of wind energy potential rather than a highly detailed probabilistic characterization of wind energy potential in preliminary studies when detailed wind speed distributions are not available [5,12].

Estimation of Wind Power Density

Wind power density (WPD) represents the amount of available wind energy per unit swept area and is a key indicator of wind resource potential. It is defined as:

$$WPD=\frac{1}{2}\rho\, E(v^3) \qquad \text{……………….(2)}$$

where ρ is the air density (kg/m³) and $E(v^3)$ denotes the expected value of the cube of wind speed.
Assuming a Weibull distribution, the expected value $E(v^3)$ can be calculated as [4]:

$$E(v^3)=c^3\,\Gamma\left(1+\frac{3}{k}\right) \qquad \text{……………….(3)}$$

where Γ(·) is the Gamma function. In this study, air density was assumed to be 1.225 kg/m³,Although air density may vary with altitude and local atmospheric conditions, the use of a standard value is considered acceptable for preliminary assessments and is not expected to significantly alter the general conclusions of the study corresponding to standard atmospheric conditions. The implications of this assumption for elevated terrain are discussed later in the paper.

Wind Speed Extrapolation with Height

To estimate wind speed at different turbine hub heights, the power law relationship was employed:

$$V(z)=V(z_{ref})\left(\frac{z}{z_{ref}}\right)^{\alpha} \qquad \text{……………….(4)}$$

where $V(z)$ is the wind speed at height z, $V(z_{ref})$ is the wind speed at the reference height z_{ref}, and α is the wind shear exponent.
In mountainous and complex terrain, the wind shear exponent is influenced by surface roughness, slope orientation, and terrain-induced flow distortion, and is generally higher and more variable than in flat or coastal regions [7,10]. In this study, a representative value of $\alpha=0.20$ was adopted for preliminary analysis, consistent with values reported for inland mountainous environments.

Methodological Limitations

It should be noted that the use of monthly mean wind speed data limits the ability to capture short-term wind variability and extreme wind events, which can significantly influence wind energy production due to the cubic dependence of power on wind speed. Furthermore, the absence of wind direction and turbulence intensity data restricts detailed micrositing and structural load analyses. Consequently, the results obtained in this study should be interpreted as indicative rather than definitive and are intended to guide future high-resolution measurements and advanced modeling efforts.

RESULTS AND DISCUSSION

Wind Speed Characteristics

The statistical analysis of the monthly mean wind speed data indicates that the overall mean wind speed at the reference height is approximately 4.35 m/s. This value reflects a low-to-moderate wind regime near the surface. The seasonal variation of wind speed is illustrated in Figure 1, which shows relatively higher wind speeds during the winter and spring months and lower values during the summer period.

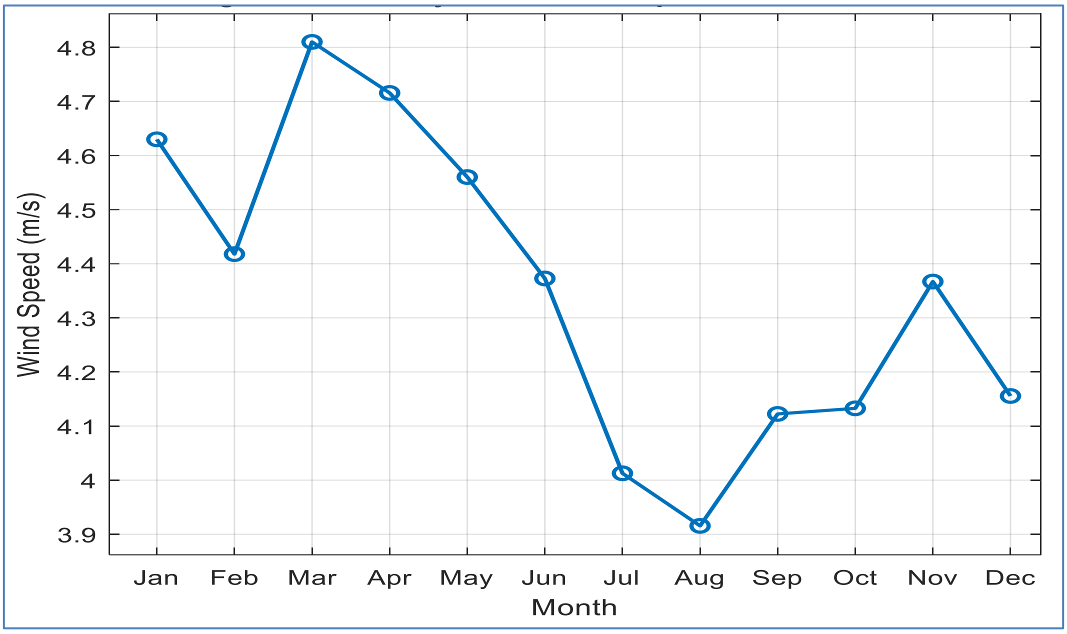

Figure 1. Long-term monthly mean wind speed in the Jabal Al Gharbi region.

The observed seasonal behavior suggests a moderate variability throughout the year, without sharp fluctuations. The annual mean wind speed variation over the study period (2011–2020) is presented in **Figure 2**. The results show noticeable inter-annual variability; however, no consistent increasing or decreasing trend can be identified from the available data.

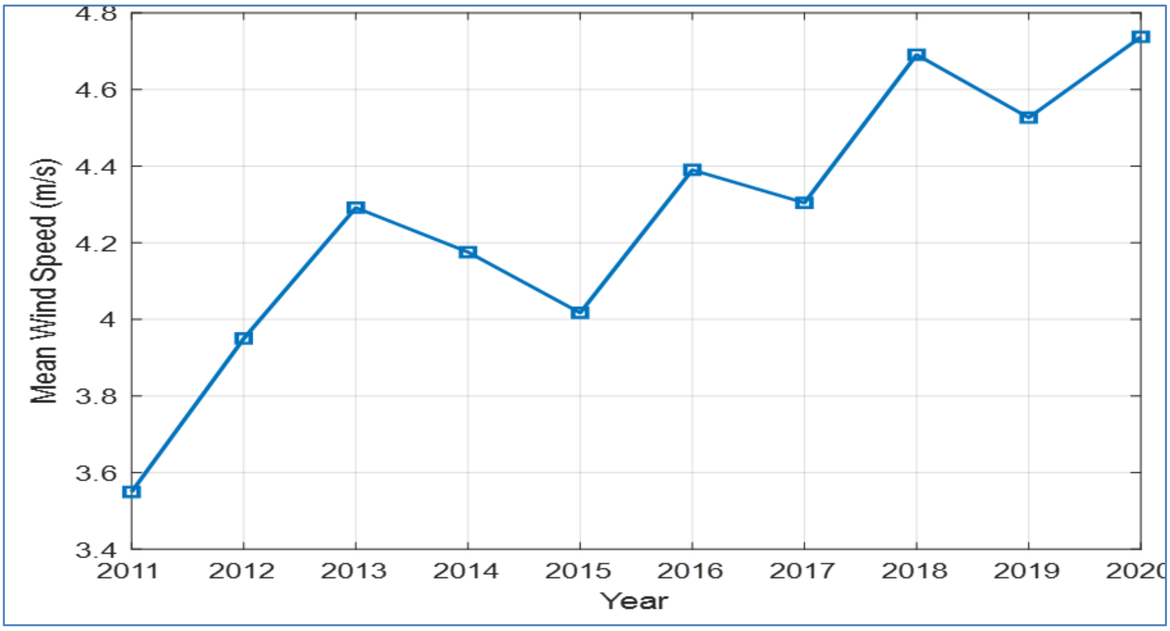

Figure 2. Annual mean wind speed variation at Yefren station (2011–2020)Wind Speed Distribution and Wind Power Density.

The probabilistic representation of wind speed using the Rayleigh distribution is illustrated in

Figure 3. Based on the estimated Weibull parameters, the scale parameter was calculated as 4.90 m/s, while the shape parameter was fixed at k = 2.

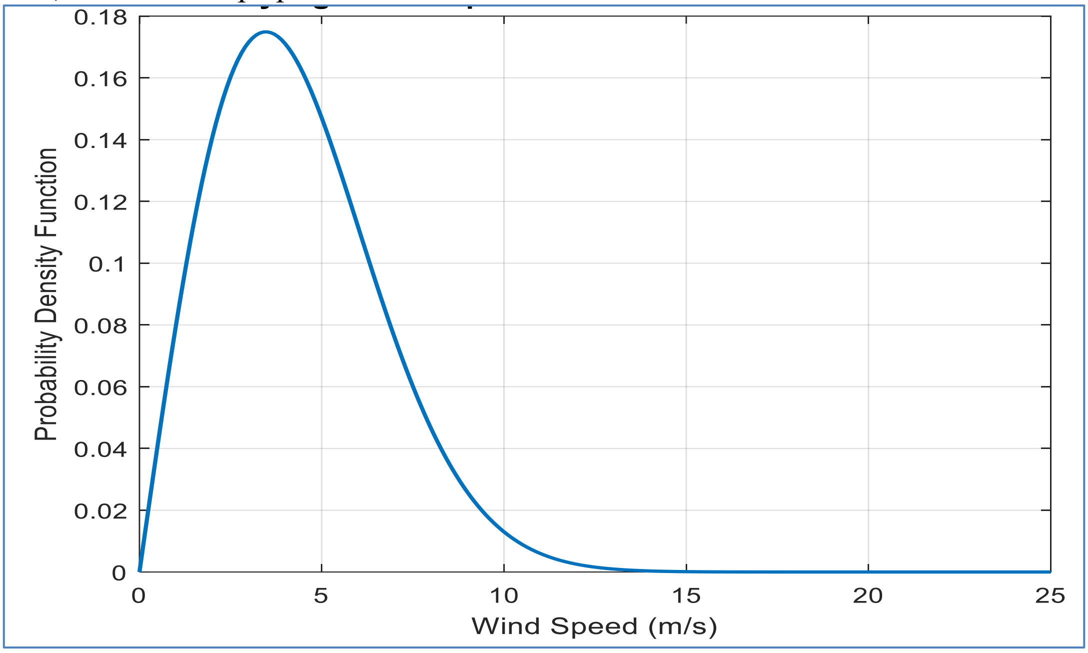

Figure 3. Rayleigh wind speed probability distribution for the Jabal Al Gharbi region.

Using these parameters, the wind power density at the reference height was estimated to be approximately 96 W/m². This value represents the mean available wind power per unit swept area and provides a quantitative indicator of the wind energy potential at the study site.

Effect of Hub Height on Wind Speed

The extrapolation of wind speed to different turbine hub heights reveals a significant increase in wind speed with height. As shown in Figure 4, the estimated mean wind speed increases from 4.35 m/s at the reference height to approximately 6.00 m/s, 6.59 m/s, and 6.89 m/s at hub heights of 50 m, 80 m, and 100 m, respectively.

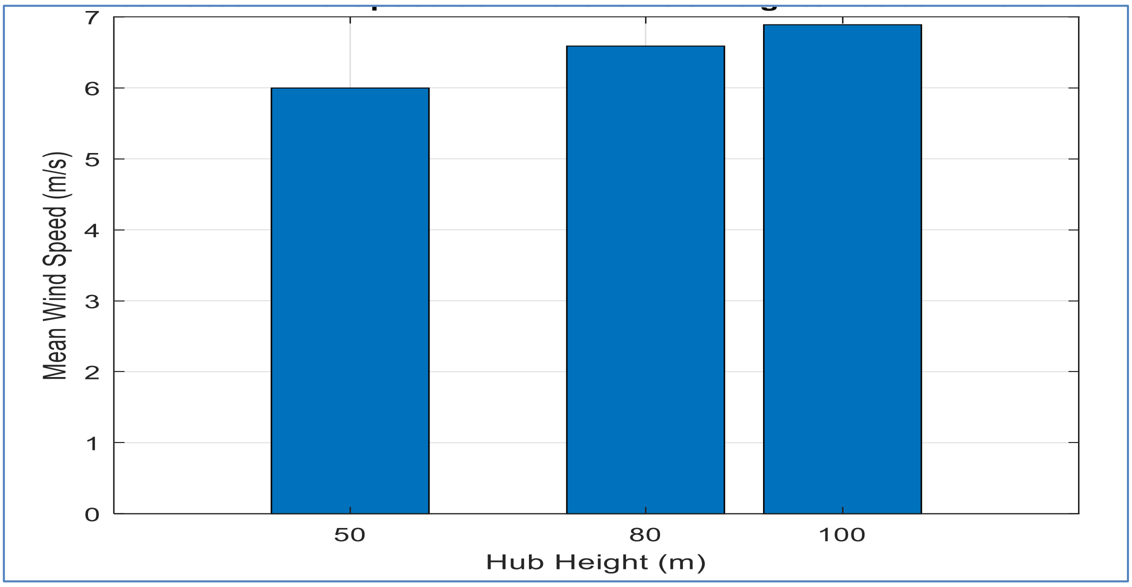

Figure 4. Estimated mean wind speed at different turbine hub heights in the Jabal Al Gharbi region.

These results clearly demonstrate the strong influence of vertical wind shear in the study area and highlight the importance of hub height selection in mountainous regions.

Discussion

The results indicate that near-surface wind speeds in the Jabal Al Gharbi region are moderate; however, the pronounced increase in wind speed with height suggests that the wind energy potential improves significantly at elevated hub heights. This behavior is characteristic of mountainous and complex- terrain environments, where orographic effects and enhanced exposure to prevailing winds can substantially modify the vertical wind profile [7].

The wind power density value obtained at the reference height falls within the lower range of commonly used wind power classification schemes. Nevertheless, it is important to note that wind power density estimates derived from monthly mean wind speed data tend to be conservative, as they do not fully capture short-term high wind events due to the cubic dependence of wind power on wind speed [12]. Consequently, the actual exploitable wind energy potential may be higher Although the estimated wind power density at the reference height is relatively moderate, the significant increase in wind speed at higher hub heights substantially improves the expected annual energy production. This explains the apparent consistency between the moderate near-surface wind resource and the favorable indicative economic performance obtained in the techno-economic assessment than indicated by the present estimates.

The strong sensitivity of wind speed to hub height, as shown in Figure 4, has important implications for wind energy system design in mountainous terrain. Taller towers can significantly enhance energy production, potentially offsetting the disadvantages associated with moderate near-surface wind speeds. Similar findings have been reported in recent studies focusing on wind energy deployment in complex and mountainous regions [11,15].

A brief comparison with coastal wind regimes suggests that coastal areas typically offer more uniform and higher wind speeds near the surface. However, the results of this study demonstrate that mountainous regions can partially compensate for lower surface wind speeds through increased vertical wind shear and optimized turbine placement. This highlights the importance of terrain-specific assessment rather than generalized exclusion of mountainous areas from wind energy planning.

Although the annual mean wind speed values appear to exhibit a gradual increase over the study period, this behavior should not be interpreted as a long-term climatic trend. The analysis is based on monthly averaged wind speed data and covers a relatively short time span of ten years, which is insufficient for detecting statistically significant climate-scale trends. The apparent increase is therefore more likely attributed to natural inter-annual variability and the smoothing effect introduced by temporal averaging, rather than a persistent change in regional wind climate.

Overall, the findings confirm that the Jabal Al Gharbi region exhibits wind characteristics that are technically suitable for wind energy applications at elevated hub heights, supporting its consideration for further detailed investigation using high-resolution measurements and advanced numerical modeling techniques.

Techno-Economic Assessment

The techno-economic assessment aims to evaluate the preliminary economic feasibility of deploying wind energy systems in the Jabal Al Gharbi region based on the estimated wind characteristics and typical onshore wind turbine parameters. Given the data limitations and the exploratory nature of the study, the analysis focuses on indicative economic indicators rather than a detailed investment feasibility study.

Assumed Wind Turbine and Economic Parameters

The economic evaluation was conducted for a representative 2 MW onshore wind turbine, which is commonly used in medium-scale wind energy projects and is suitable for inland and mountainous regions. The selected hub height was 100 m, corresponding to the height at which favorable wind conditions were identified in the previous section.

Table2: main technical and economic assumptions adopted in the analysis are summarized as follows:

Parameter	Value
Rated power:	2 MW
Hub height:	100 m
Turbine lifetime:	20 years
Estimated capacity factor:	22-27%(assumed based on typical ranges reported for medium-scale onshore wind systems in moderate wind regimes)
Capital cost:	6,860 LYD/kW
Operation and maintenance cost:	2.5% of capital cost per year
Discount rate:	8%

The capital cost value corresponds to typical onshore wind installation costs reported in recent techno-economic studies and was converted to Libyan Dinar using an assumed exchange rate of 4.9 LYD/USD.

Capital and Operating Costs

The total capital expenditure (CAPEX) for the selected wind turbine was calculated as:

$$\mathbf{CAPEX = P_{rated} \times C_{unit}}$$

where P_{rated} is the rated power in kilowatts and C_{unit} is the unit capital cost. For a 2 MW turbine, the total capital cost was estimated to be approximately 13.72 million LYD. The adopted capital cost assumptions are based on typical onshore wind installation costs reported in recent renewable energy economic studies [2,14].

The annual operation and maintenance (O&M) cost was assumed to be 2.5% of the total capital cost, resulting in an estimated annual O&M cost of approximately 343,000 LYD/year. This assumption is consistent with values commonly reported for medium-scale onshore wind energy systems [2,14].

Annual Energy Production

The annual energy production (AEP) was estimated using the following relationship:

$$\mathbf{AEP = P_{rated} \times CF \times 8760}$$

where CF is the capacity factor and 8760 represents the number of hours in a year.

Based on the estimated wind speed at a hub height of 100 m and conservative assumptions regarding turbine performance in complex terrain, the expected AEP was estimated to range

between:
3.85 GWh/year for a capacity factor of 22%
4.73 GWh/year for a capacity factor of 27%
The adopted capacity factor range was selected based on values commonly reported in the literature for medium-scale onshore wind systems operating under moderate wind conditions [14,15]. These values also reflect uncertainty associated with wind variability and terrain-induced effects.
Levelized Cost of Energy
The levelized cost of energy (LCOE) was used as the primary indicator for assessing economic feasibility. LCOE represents the average cost of electricity generated over the lifetime of the system and is expressed as:

$$\mathbf{LCOE} = \frac{\textbf{Total lifetime cost}}{\textbf{Total lifetime energy production}}$$

This indicator is widely used in renewable energy economic assessment studies due to its ability to compare different power generation technologies on a consistent basis [2].
Based on the assumed capital and operating costs and the estimated annual energy production, the LCOE for the proposed wind energy system in the Jabal Al Gharbi region was estimated to lie in the range of:

$$\mathbf{LCOE = 0.34 - 0.49, LYD/kWh}$$

This range reflects uncertainty in energy production estimates and conservative assumptions adopted in the analysis.
Economic Interpretation
The estimated LCOE values indicate that wind energy systems in the Jabal Al Gharbi region can be economically viable, particularly for medium-scale or decentralized applications. Although the cost of electricity is higher than that typically achieved by large-scale coastal wind farms, the results suggest that mountainous terrain can support competitive wind energy projects when appropriate hub heights and turbine configurations are employed [7,15].
It should be emphasized that economic feasibility in mountainous regions is sensitive to several factors, including wind speed uncertainty, turbulence-induced maintenance requirements, accessibility, and grid connection costs [7,10]. Therefore, the results presented in this study should be regarded as indicative and intended to support early-stage planning and decision-making.
Future techno-economic studies should incorporate high-resolution wind measurements, site-specific turbine selection, and detailed cost breakdowns to refine the economic assessment and reduce uncertainty.

Conclusion
This study presented a preliminary wind resource and techno-economic assessment of the Jabal Al Gharbi region in western Libya, with a particular focus on evaluating the suitability of mountainous terrain for wind energy system design. The analysis was based on monthly mean wind speed data recorded at the Yefren meteorological station over the period 2011–2020 and aimed to address the lack of wind energy studies in inland and complex-terrain regions.
The statistical analysis revealed that the overall mean wind speed at the reference height is

approximately 4.35 m/s, indicating a low-to-moderate wind resource near the surface. Correspondingly, the estimated wind power density was found to be around 96 W/m². While these values suggest limited wind energy potential at low elevations, wind speed extrapolation demonstrated a pronounced increase in wind speed with height. Mean wind speeds exceeding 6.8 m/s at a hub height of 100 m highlight the significant role of vertical wind shear and orographic effects in enhancing wind energy potential in mountainous terrain.

The techno-economic assessment, conducted for a representative 2 MW onshore wind turbine, indicated that wind energy deployment in the Jabal Al Gharbi region can be economically feasible under conservative assumptions. The estimated levelized cost of energy ranged between 0.34 and 0.49 LYD/kWh, suggesting that wind energy systems in mountainous regions may be competitive for medium-scale or decentralized applications, particularly where alternative energy options are limited.

Despite these promising findings, the study acknowledges several limitations related to data resolution and terrain complexity. The reliance on monthly averaged wind speed data restricts the ability to capture short-term variability and extreme wind events, while the absence of wind direction and turbulence measurements limits detailed micrositing and structural load assessments. Consequently, the results should be interpreted as indicative and intended to support early-stage planning rather than definitive project development.

Overall, this research demonstrates that mountainous regions such as Jabal Al Gharbi should not be excluded from wind energy planning. When appropriate hub heights and design considerations are applied, such regions can offer technically and economically viable conditions for wind energy deployment. Future work should focus on high-resolution wind measurements, advanced numerical modeling, and site-specific techno-economic analyses to reduce uncertainty and support optimized wind energy development in complex-terrain environments.

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Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.