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Evaluating the Wind Potential of Coastal and Inland Locations in Oman for Power Generation

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Abstract

The potential for green energy in Oman is promising as a power generation option. Wind energy is a common type of clean energy. Oman locations demonstrate varying characteristics that indicate good scope for power generation from wind energy. The geographical features, wind speed variations, and wind directions all impact the potential for wind power generation. To explore the wind characteristics for power generation in Oman, seven locations (coastal and inland) were selected for this study. Weather data sets collected from seven meteorological stations (Qalhat, Sur, Masirah, Raysut, Marmul, Qairoon Hairiti and Thumrait) within Oman for the year 2023 were used to analyze wind speed variations, and directions, and to predict the amount of wind power generation. The results show that coastal locations such as Sur and Masirah, along with inland locations like Marmul, Qairoon Hairiti, and Thumrait, exhibit promising average wind speeds of 4.99 m/s, 5.50 m/s, 4.33 m/s, 5.22 m/s, and 5.83 m/s respectively. Conversely, Qalhat and Raysut demonstrate lower potentials with average speeds of 2.82 m/s and 2.34 m/s. The results highlight that the predominant wind directions are in line with seasonal patterns. The power generation for the high-potential locations can generate power ranging from 1.00 to 1.61MW, signifying substantial energy generation capabilities. This study reveals that the optimal condition is at Thumrait with 1.61 MW power generation. The findings of this research study underscore the strategic importance of location-specific wind assessments in advancing Oman's renewable energy agenda and highlighting the significant contribution of wind power to sustainable energy goals.

***Keywords**: Oman; power generation; renewable energy; wind direction; wind potential; wind speed

1. Introduction

Wind energy experienced significant growth globally from 2010 to 2023. Global wind capacity has increased from about 200 MW in 2010 to more than 1 GW in 2023 (Morales,.2022), as shown in Figure 1. Oman is known for its substantial oil and natural gas reserves. However, as global trends move towards sustainable green energy wherein Oman is gradually focusing on renewable energy sources. This includes wind energy since the production of wind power has gained a massive global importance. This movement is determined by both economic diversification goals and international commitments to decrease carbon emissions. Wind power presents itself as a clean practical method to reduce carbon emissions and meet the increasing energy demands, concerning climate change and the depletion of fossil fuels. That is, wind energy significantly reduces the carbon footprint by providing a clean, renewable source of power that generates electricity without producing greenhouse gas emissions, unlike fossil fuels. Oman's geographical location and topography offer significant potential for wind energy that could be transformed into electrical power using wind turbines (Danook et al., 2019). The coastal areas, particularly in the southern and southeastern parts of the country, experience strong and consistent wind patterns. According to the Global Wind Atlas (Nama Group Annual report, 2022), Dhofar and Al Wusta regions have average wind speeds that exceed 6 m/s at 100 meters above ground level. This is considered favourable for wind energy generation.

Wind energy potential evaluation is needed for the development of wind energy projects. In Oman, extensive wind measurement campaigns were conducted to identify high-potential areas. Data sets from these assessments cover the wind speed, direction, and variability at 50 m and 100 m heights (Alnuaimi et al., 2014). Table 1 below shows wind speed data sets from four regions in Oman.

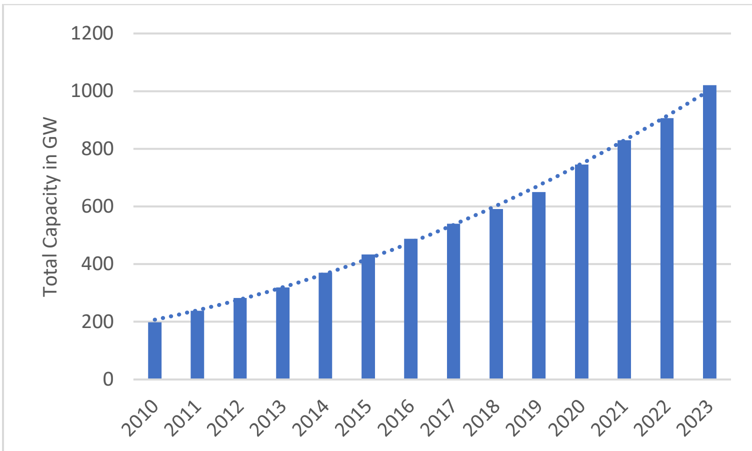

Figure 1: Installed wind turbine capacity from 2010 to 2023

Table 1: Wind speed data from four regions in Oman

Regions	Average wind speed (m/s) at 50m	Average wind speed (m/s) at 100m	Turbulence intensity
Dhofar	6.5	7.2	Low
Al Wusta	6.3	7.0	Low
Musandam	5.5	6.0	Medium
Al Sharqiyah	5.0	5.5	Medium

Oman has good renewable energy strategies and plans to include solar, wind, and other sources. These energy sources can be analyzed in terms of their cost and environmental impacts. The levelized cost of electricity (LCOE) is a required measure for comparing energy sources (Al-Badi et al., 2013). This measure is used to compare the cost of generating electricity from renewable energy sources. It represents the per-unit cost (usually expressed in dollars per megawatt-hour, or $/MWh) of building and operating a generating plant over its lifetime, considering both the initial capital costs and the operational and maintenance expenses, and the projected electricity production. Table 2 shows the LCOE of wind, solar PV, and natural gas in Oman.

Table 2: The levelized cost of electricity (LCOE) in Oman (Al-Badi et al., 2013)

Energy Source	LCOE (USD/MWh)
Wind	40-60
Solar PV	30-50
Natural Gas	50-70

Wind electricity has a lower environmental impact if compared with fossil fuels. It produces no greenhouse gas emissions for the duration of operation and calls for much less water. However, it's miles vital to keep in mind elements like land use and influences on the natural world, especially birds and bats. Wind turbine technology has advanced significantly to improve efficiency and reduce costs. Modern turbines are equipped with larger rotors and taller towers.

This allows them to capture more wind energy even at lower wind speeds. For Oman, the adoption of these advanced technologies is needed to maximize the potential of its wind resources.

As of 2024, Oman’s outstanding wind energy project is the Dhofar Wind Power Project (Dhofar Wind Farm). It is the first larger-scale wind farm in Oman. that was commissioned in 2019. This project has an installed capacity of 50 MW and is composed of 13 wind turbines (Global Wind Atlas). The project was established by the Rural Areas Electricity Company (Tanweer) in corporation with Masdar. It is a significant initiative in Oman's renewable energy sector.

Oman has set ambitious targets for green renewable energy. The government’s policies include financial incentives, regulatory support, and international collaborations to attract investments in the renewable sector. According to the current trends and government policies, wind energy capacity in Oman is expected to grow significantly. Based on the 100 m tall MET masts, the phase I projected projects (Duqm and Jalan Bani Bu Ali) and phase II projected projects (Ras Madraka and Sadah) are displayed in Table 3.

Table 3: Projected wind farms in Oman (2020-2030) (Global Wind Atlas)

Phase	Projected wind farms			
I	Duqm-I	Duqm-II	Jalan-I	Jalan-II
II	Ras Madraka-I	Ras Madraka-II	Sadah-I	Sadah-II

To put Oman’s wind energy development in a global context, it is useful to compare it with leading wind energy markets. Table 4 highlights key statistics from leading countries in wind energy.

Table 4: Comparative analysis of global wind energy trends (Ochoa et al., 2019)

Country	Installed Capacity (GW)	Major Wind Farms
China	474.6	Gansu Wind Farm
United States	150.455	Alta Wind Energy Center
Germany	69.457	Horns Rev Wind Farm
India	44.736	Muppandal Wind Farm
Oman	0.05	Dhofar Wind Power Project

Oman boasts a diverse climate. The climate of Oman results in varied wind patterns. This research study explores the wind energy potential in Oman by assessing the wind characteristics at seven selected locations (Band et al., 2021) . The wind dynamics and weather properties are required for optimizing wind energy harvesting systems in Oman. They are supporting the country's renewable energy initiatives and contributing to global climate change mitigation efforts.

Despite the acknowledged potential of wind energy, the existing research often lacks a detailed, location-specific analysis of wind patterns and their implications for wind power generation in Oman. The main wind masses affecting Oman exhibit dynamic and diverse patterns influenced by meteorological factors. This leads to distinct wind masses, magnitudes, directions, and potential utilization throughout the year (Charabi et al., 2011). Oman experiences a combination of wind types across the four seasons, including the Shamal, Sharqi, and Monsoon winds. Each of these wind types is characterized by unique origins and atmospheric dynamics (Jervase and Al-Lawati, 2012). Figure 2 shows the wind masses and their directions over Oman. During the winter season (December to February), the Shamal winds from the northwest bring cooler temperatures and increased wind speeds. This is mainly along the northern coastal regions. On the other side, the southern regions of Oman experience the influence of the southeast Monsoon winds. This is called Khareef, and its effect is during the summer period (June to September). The transitional seasons of spring and autumn see the Sharqi winds, which can be more often from the east (Rashki et al., 2019). These seasonal versions in both wind velocity and path require radical research to optimize wind energy harvesting structures in Oman. However, the latest studies have no longer sufficiently addressed the seasonal versions in wind velocity and direction and their effect on wind energy ability across Oman areas. This gap highlights the want for a thorough investigation to optimize the deployment of wind farms and beautify the efficiency of wind strength era inside the country.

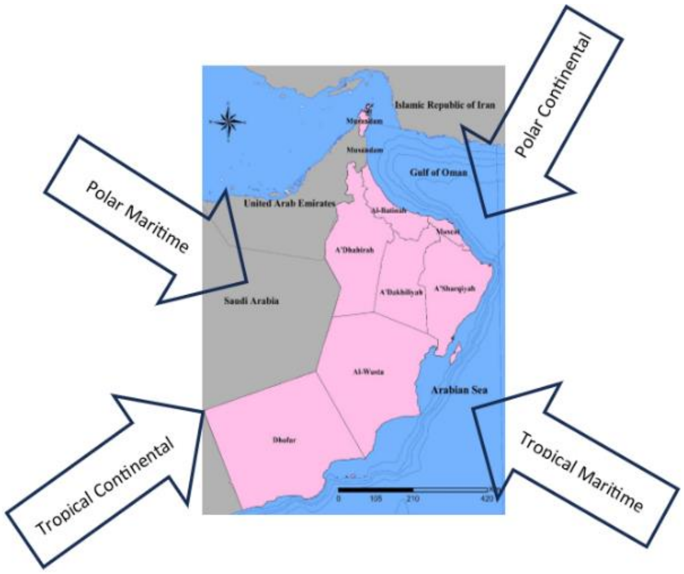

Figure 2: Wind masses directions over Oman (Al-Awadhi and Mansour, 2015)

The changing wind properties and speed magnitudes throughout Oman present an important potential for harnessing wind energy. In 2023, Oman advanced its renewable energy initiatives by focusing on wind power generation. Its strategic geographic location, with an extensive coastline and diverse terrain, provides significant opportunities for developing wind farms and other renewable energy facilities (Reve, 2019). Wind energy generation usually reaches its maximum during the winter and transitional times, at which the wind speeds are relatively higher. This is particularly along the coastal areas and mountain regions. Advanced technologies and developments in wind turbine systems enhanced further the efficiency and viability of wind power generation. This can enable Oman to capitalize on the plentiful wind resources sustainably.

Understanding the variations in wind direction and speed is needed for effective planning and deployment of wind farms (Energy Intelligence). This research study investigates how these variations in wind speed and direction impact the energy potential for wind power generation at seven locations in Oman. The selected locations that were chosen for this study are based on their distinct wind characteristics during 2023. The data sets were collected from meteorological stations that are strategically placed across Oman. The availability of these data sets, their precision and relevance of the 2023 made it a suitable basis for this study.

Oman's vision runs parallel with global initiatives to mitigate climate change and minimize the dependency on non-renewable energy resources (Global Wind Atlas). The commitment of Oman to increase the proportion of renewable energy in its overall energy consumption is evident in its plans and strategies to generate around 30% of its energy from renewable sources by 2030. More specifically, 6.5% is expected to come from wind energy, 21% from solar energy and 2.5% from other renewable sources (Al-Hinai et al., 2021). This focus and movement towards wind power reflect Oman's strategic efforts to leverage its geographical advantages, at the same time to contribute to the global movement toward a greener and more sustainable energy landscape (Terrell et al., 2012). The objective of this research study is to evaluate wind energy potential at seven selected locations in Oman. The research covers geographic and climatic conditions, and offers a detailed analysis of wind speed variations, wind direction fluctuations, and predicted power outputs. This study backs Oman's objectives of decreasing its dependency on fossil fuels, increasing the variety of its energy sources, and investigating wind power as a vital element of its renewable energy plan.

2. Literature Review

Oman has made substantial strides in evaluating its wind energy capability, reflecting global advancements in generation and technique (Study on Renewable Energy Resources Oman, 2008). Initially, wind power measurements in Oman utilized simple anemometer structures. However, these strategies have advanced into more superior distance sensing technologies, improving the accuracy and effectiveness of wind property critiques (Gulben et al., 2019). Oman's drive to diversify its electricity resources and reduce its dependence on fossil fuels underpins those advancements.

Numerous researchers have assessed the wind electricity ability throughout Oman regions, thinking about each economic feasibility and environmental advantage. Research has aimed to better understand Oman's wind energy potential and the impact of wind path versions on wind strength output. Comprehensive tests have identified Thumrait, Qairoon Hairiti, Masirah, and Sur as promising sites for economically harnessing wind energy (Al-Badi, 2011). These studies have highlighted the great capability for wind energy technology, mainly in coastal regions in which wind speeds are greater favorable. An attention on offshore wind energy resources has found out that offshore wind generators should produce substantially more power than onshore mills, specifically throughout top strength call for in the summer time (Al-Hinai et al., 2021). This strategic gain emphasizes the better electricity yield from offshore locations and shows the improvement of offshore wind farms to meet strength demands.

Broader estimations of renewable strength assets in Oman, which include sun, wind, and tidal strength, have discovered that wind electricity potential is highest along the southeastern coasts, positioning wind power as a main contributor to Oman's renewable power portfolio alongside solar energy (Hereher and El Kenawy, 2020). Evaluations of wind energy generation prices throughout 21 places in Oman with the use of special wind turbine prototypes, indicated decreased expenses in the southern and middle regions in comparison to the north, making these areas more economically viable for wind power projects (Al-Badi A and Al-Badi H., 2010). Analyzes of wind power era capacity in northern and southern Oman have identified the most reasonably priced, efficient, and dependable wind turbines for each location and quantified potential CO_2 emissions discounts, underscoring the environmental advantages of wind strength adoption (Charabi and Abdul-Wahab, 2020).

The financial viability of the usage of wind strength to generate hydrogen in Oman has also been explored. Evaluations of wind strength capacity, levelized fee of energy, predicted hydrogen manufacturing, and levelized charge of hydrogen throughout certainly one-of-a-kind locations concluded that wind-to-hydrogen manufacturing holds massive capacity, specifically in Masirah and Thumrait (Ahshan et al., 2022). The ability for small wind turbines in Oman has been investigated, revealing appropriate potential for numerous applications because of favourable wind conditions, assisting the feasibility of regionalized electricity generation structures in a way off or rural areas (Ahshan et al., 2018). An assessment of renewable electricity resources in Oman emphasized the importance of developing wind electricity to diversify Oman's power mixture (Kazem, 2011).

Wind information (wind speeds and wind directions) from seven distinctive weather stations in Oman has been analyzed. The usage of new methods that calculate fundamental wind pace based totally on a three-second gust was considered by Almaawali, S. (Almaawali, 2017) with effects regular with traditional strategies, demonstrates the reliability of those new strategies. Wind pace statistics accrued and analyzed for the part of Oman turned into used to simulate wind speeds at four locations, focusing at the financial sustainability of wind projects in areas like Duqm and Jalaan Bani Bu Ali (Sulaiman et al., 2002)(Nama Group Annual Report, 2021) . This highlighted the significance of area choice in maximizing wind energy capacity to assist renewable power projects. Seasonal versions in wind path and speed decide the reliability and performance of wind generators (Hoxha et al., 2023). Computational models, satellite statistics, and on-location measurements simulate wind houses, velocity, and route, supplying a clean image of the most beneficial wind farm placement and electricity output growth. These outcomes underscore the want for comprehensive wind assessment to help strategic wind electricity improvement in Oman.

Wind energy potential in Oman has been extensively studied showing promise. Onshore assessments identified Thumrait, Qairoon Hairiti, Masirah, and Sur as economically viable sites for wind power generation (Al-Badi, 2011). Offshore wind turbines in Oman's territorial seas could produce at least 1.34 times more energy than land-based alternatives, particularly during peak summer demand (Al-Hinai et al., 2021). A comprehensive study using climatic and socioeconomic factors found that 3.2% of Oman's territory is suitable for wind energy development, showing that the most promising sites along the southeastern coast (Hereher and El Kenawy, 2020). Solar energy also shows potential in Oman, with 4.4% of the country suitable for sustainable use. Similar assessments in coastal Pakistan identified Pasni and Jivani as optimal locations for wind energy generation, demonstrating the importance of site-specific evaluations in coastal regions (Al-Yahyai et al., 2010).

Oman's numerous geographies create varied wind and climate properties. High wind speeds are recorded alongside the coastal areas, at the same time as the northern and western inland regions have the lowest wind speeds. Research continually indicates widespread wind strength ability in coastal areas from Qalhat to Raysut and slight ability in inland areas just like the Hajar Mountains (The Open Map, Mapcarta) . These researches suggest that with strategic funding and improvement, wind strength can play an essential role in Oman's transition to a greater sustainable and renewable power destiny.

Oman has advanced in wind energy research. Studies identify key regions like Thumrait, Masirah, and Sur as promising for wind power, especially in coastal areas. Offshore turbines are found to generate more energy than onshore, particularly during peak summer demand. This research supports Oman's goal of diversifying energy sources, reducing reliance on fossil fuels, and exploring wind power as a key component of its renewable energy strategy.

3. Methodology and Datasets

The main objective of this research work is to evaluate the wind power potential at seven selected locations in Oman. The effects of wind speeds and directions at these locations on the wind power potential are also considered for evaluation. During 2023, the meteorological stations gathered plentiful amounts of wind speed and direction data sets. For this research study, these meteorological data sets were utilized for wind power prediction. The latest data sets of 2023 are the latest updated data sets that could be selected and compared with findings from other studies, to reflect current findings of weather potential. Geographical features and seasonal variations influence also wind dynamics, considering the differences between coastal and inland locations of Oman.

Oman's varied geography creates diverse wind patterns. This makes it an attractive location for studying wind power. A network of 32 meteorological stations has been developed to cover the weather patterns across Oman. These stations are connected to the head office at Muscat International Airport through advanced technical communications. According to these meteorological stations, high wind speeds are recorded along the coast, while the northern and western regions have the lowest wind speeds. The high wind power potential is mainly in coastal locations from Qalhat to Raysut and moderate potential in inland regions like the Hajar Mountains (Band et al., 2021) . For this research study, the seven locations selected for this study are shown in Figure 3; three inland locations (Marmul, Qairoon Hairiti and Thumrait) and four coastal locations (Qalhat, Sur, Masirah and Raysut). The selection approach is to capturing a diverse range of climatic conditions and geographical features within Oman. These locations are targeted to have a good wind potential for future consideration of wind farms (Study on Renewable Energy Resources Oman, 2008). Table 5 shows the characteristics of the selected locations (Dhofar Wind Power Project). The WMO (World Meteorological Organization) Guidelines are used to provide comprehensive standards for the collection and analysis of meteorological data, including wind speed and direction measurements (Hussain et al., 2023). These guidelines confirm that data collection is consistent, reliable, and can be compared globally.

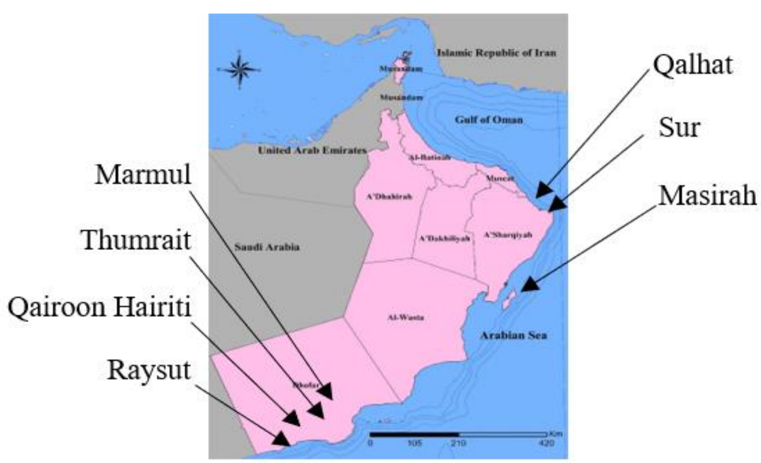

Figure 3: Locations of selected locations on Oman map (Al-Awadhi and Mansour, 2015)

Table 5: Characteristics of the selected locations

Location	Type	Longitude (ºE)	Latitude (ºN)	Height above sea level (m)
Qalhat	Costal	59° 22' 12"	22° 42' 10"	12
Sur	Costal	59° 48' 33"	22° 53' 33"	14
Masirah	Costal	58° 47' 22"	20° 25' 13"	19
Raysut	Costal	53° 91' 67"	16° 91' 67"	33
Marmul	Inland	55° 18' 33"	18° 13' 33"	269
Qairoon Hairiti	Inland	54° 5' 10"	17° 15' 5"	878
Thumrait	Inland	54° 01′ 58″	17° 40′ 01″	467

The wind energy potential assessment involves analyzing the collected data sets and determining the wind speed distribution and directions at each location. Statistical methods for wind speed magnitudes and directions are employed to describe the wind properties. This analysis is to identify the most promising locations for wind power generation, considering the predicted wind energy potential. This prediction concerns the same GE 3.8 MW wind turbine models installed at Dhofar Wind Farm in Oman. The technical specifications of these GE 3.8 MW wind turbine systems are listed in Table 6.

Table 6: GE 3.8 MW Technical specifications

Turbine Model	Rated output (MW)	Hub height (m)	Rotor diameter (m)	Number of blades	Cut-in wind speed (m/s)	Cut-out wind speed (m/s)
GE 3.8-130	3.80	85	130	3	3	25

4. Results and Discussions

The results of this study cover the analyses of wind speed variation, wind direction variation, and predicted power output. This provides a clear view of wind energy generation in Oman. The wind speed variations over time and their impact are essential for optimizing renewable energy production. Similarly, analyzing the variations in wind direction assesses the stability and efficiency of wind farms under weather conditions. Correlating these factors with predicted power output, can refine forecasting models and enhance the reliability of wind energy as a sustainable power source.

4.1 Wind speed variation

Wind speed variation shows the changes in wind speed that occur over the year 2023. The wind speed can vary due to; changes in atmospheric pressure, temperature gradients, terrain features, and the presence of weather systems such as high and low-pressure systems, fronts, and storms. Figures 4 to 10 show the wind speed variations of Qalhat, Sur, Masirah, Raysut, Marmul, Qairoon Hairiti and Thumrait locations, respectively, during 2023. The red-coloured lines represent the cut-in speed of 3 m/s for the GE 3.8 wind turbine model, while the green-coloured lines represent the average speeds.

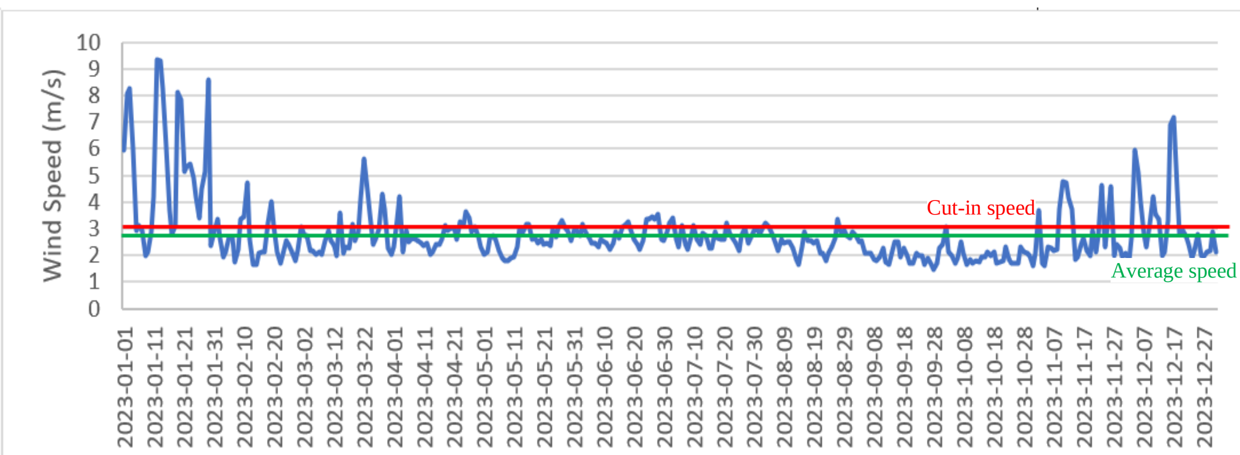

Figure 4: Wind speed variations at Qalhat location

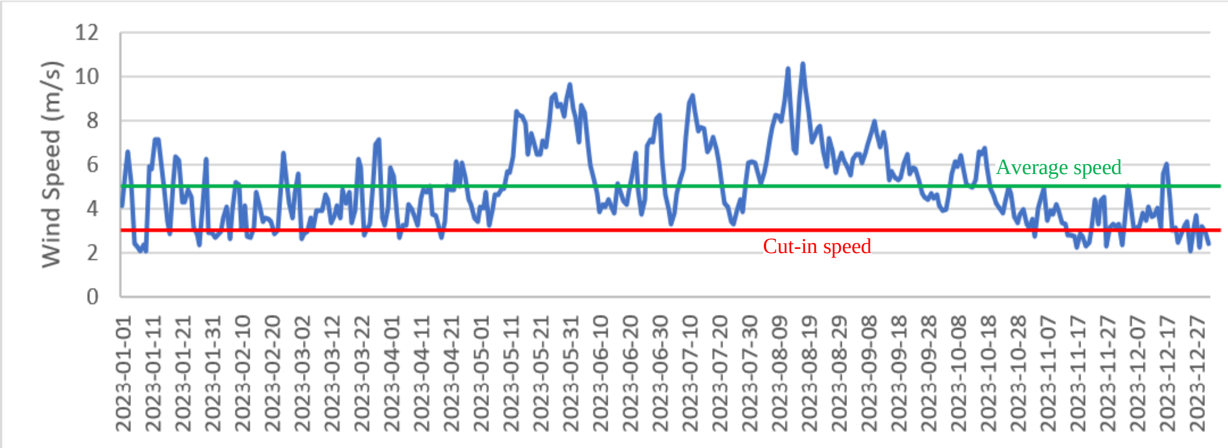

Figure 5: Wind speed variations at Sur location

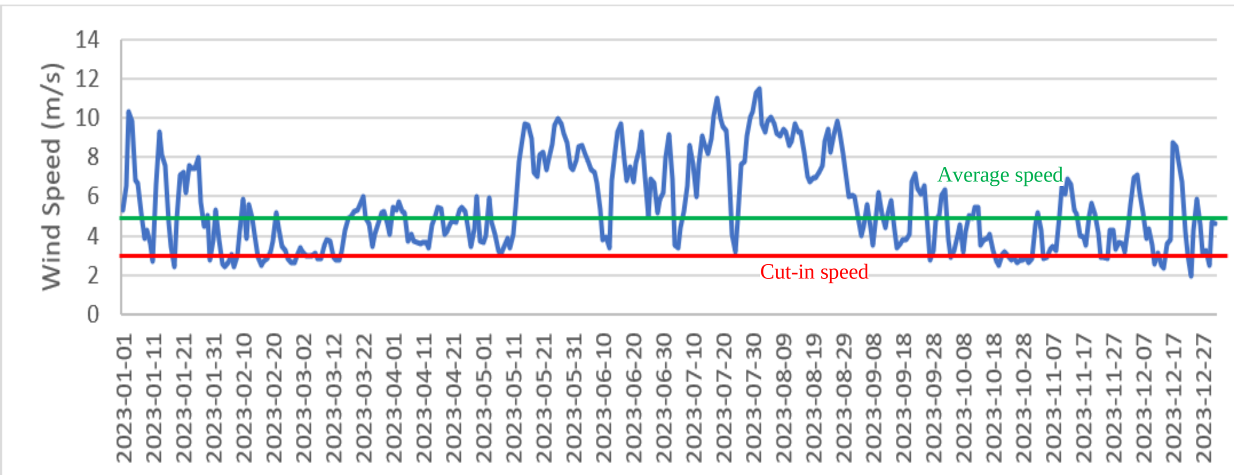

Figure 6: Wind speed variations at Masirah location

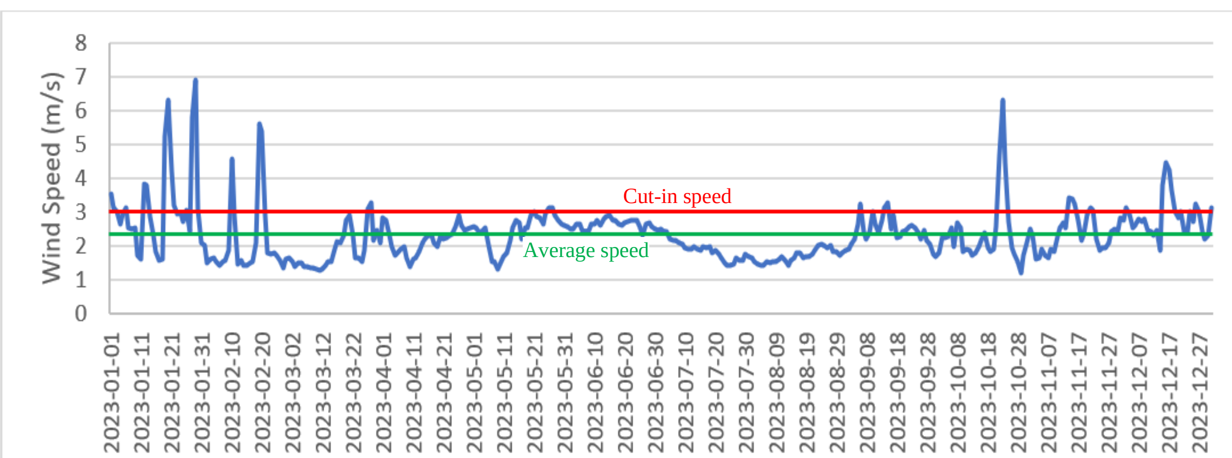

Figure 7: Wind speed variations at Raysut location

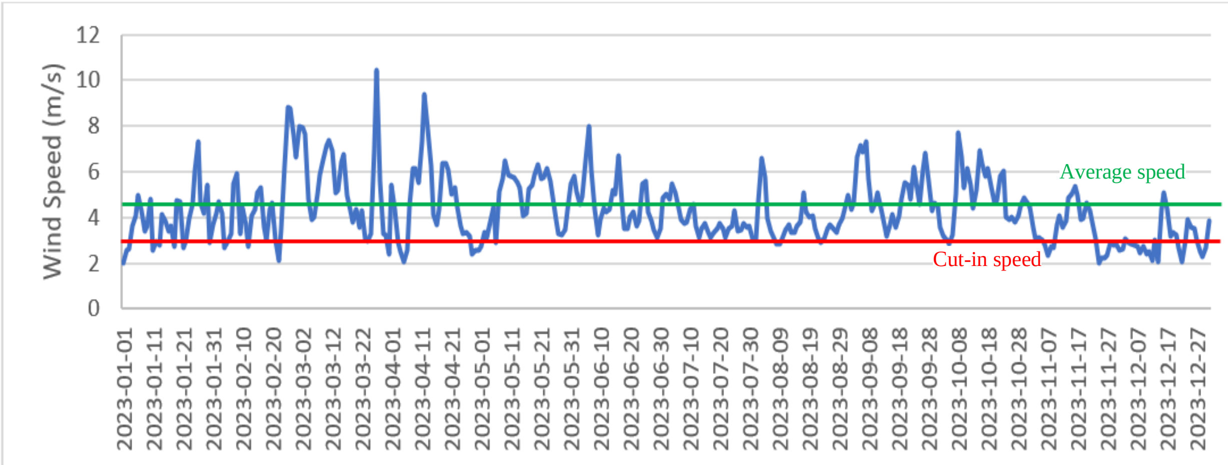

Figure 8: Wind speed variations at Marmul location

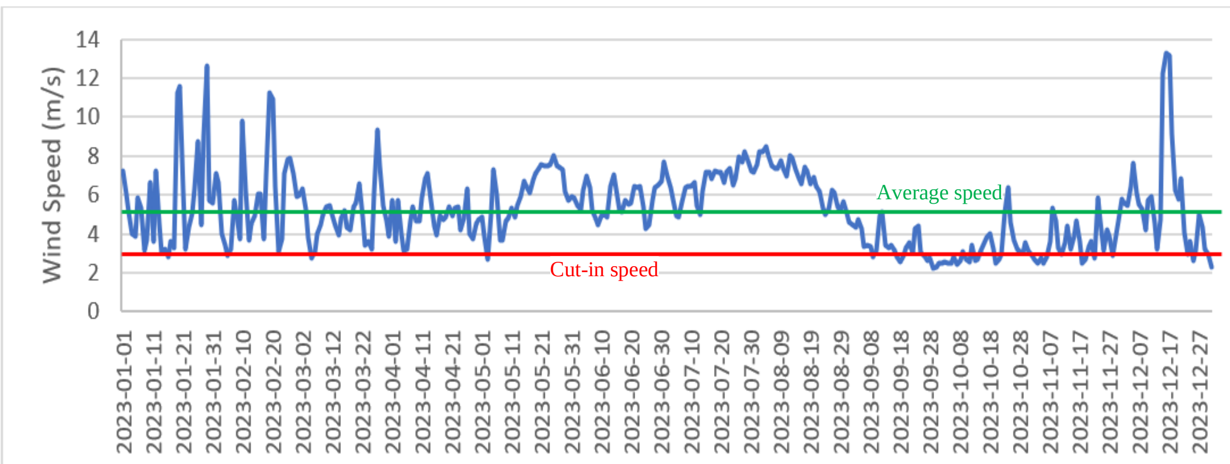

Figure 9: Wind speed variations at Qairoon Hairiti location

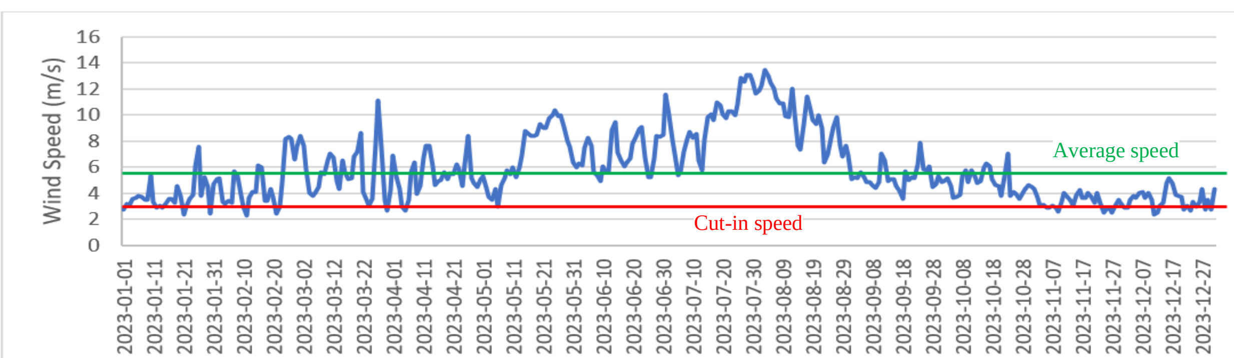

Figure 10: Wind speed variations at Thumrait location

The wind speed variation in Qalhat is nearly low most of the year, with some higher values throughout January and December. The average wind speed is 2.819 m/s less than the cut-in speed of GE 3.8 MW wind turbines. This shows that Qalhat has less potential for wind energy. Raysut has the same issue as Qalhat. The wind speed variation is almost low most of the year with an average wind speed of 2.34 m/s. This shows that Raysut has also less potential for wind energy. The wind speed variation in Sur is high during the summer months with a good amount in the rest of the year. The average wind speed is 4.996 m/s much higher than the cut-in speed of GE 3.8 MW wind turbines. This shows that Sur has a very good potential for wind energy. Masirah shows a good wind speed variation during the year, with higher values during the summer and winter months. The average wind speed is 5.50 m/s much higher than Sur, showing a very good potential for wind energy.

Marmul and Qairoon Hairiti show consistent high wind speed variations throughout the year. The average wind speeds are 4.33 m/s and 5.22 m/s, respectively, higher than the cut-in speed of GE 3.8 MW wind turbines. This gives both Marmul and Qairoon Hairiti a good potential for wind energy. Finally, Thumrait shows the highest average wind speed of 5.83 m/s, much higher than the cut-in speed. The wind speed variation is almost high most of the year, which shows that Thumrait has the highest potential for wind energy. Considering these results, a comparative analysis of the average wind speeds among the selected seven locations in Oman is shown in Figure 11.

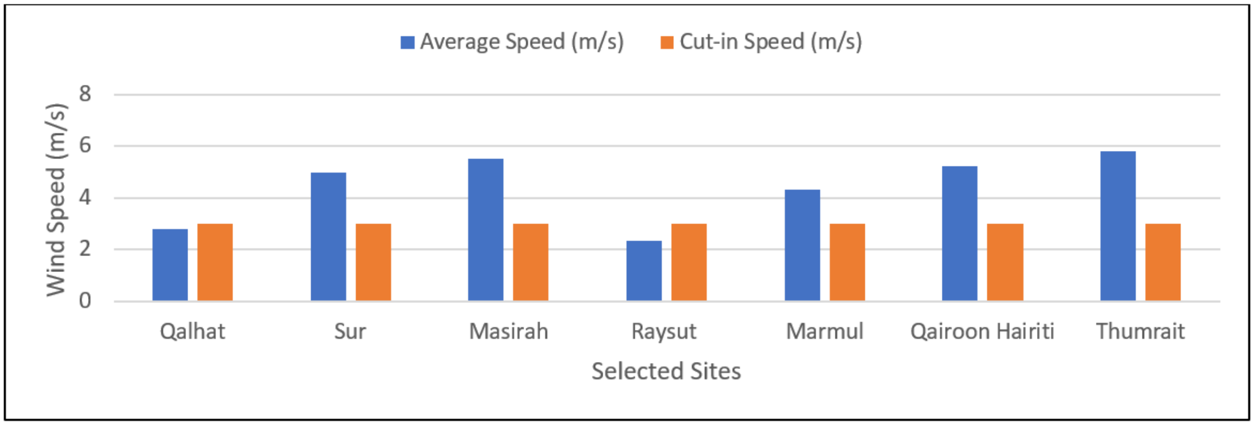

Figure 11: Average wind speeds comparison

Figure 11 gives a comparison of the seven selected locations when examining the average wind speeds versus the cut-in speeds. There is considerable variation among the locations as some locations experience average wind speeds significantly higher than the cut-in speed of 3 m/s. This indicates favourable conditions for power generation potential. Conversely, two locations (Qalhat and Raysut) have average wind speeds below the cut-in speeds. This suggests periods where turbines may not be operational due to insufficient wind.

A descriptive analysis is made to compute basic descriptive statistics at each location, considering the data sets on wind speed gathered from these meteorological stations during the year 2023 for 365 days. These statistics are then compared across the seven locations to clarify the central tendency, variability, and distribution of wind speeds.

Table 7 shows this descriptive statistics analysis of wind speed data sets of the selected locations. The Average value is calculated using the formula provided, which aggregates the daily average wind speeds to determine the central tendency.

$$Average = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{1}$$

where x_i represents each value (daily average speed) in the dataset and *n* is the total number of values (number of days in 2023).

The median for the odd number of observations is the middle value since year 2023 is 365 days.

$$Median = x_{\left(\frac{n+1}{2}\right)} \quad \text{for the dataset is: } x_1, x_2, \ldots, x_n \tag{2}$$

The variance measures the dispersion of the data set, from the data set average μ.

$$\sigma^2 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \mu)^2 \tag{3}$$

While the standard deviation is the square root of the variance, that provides a measure of the average distance from the Average.

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \mu)^2} \tag{4}$$

Finally, the skewness measures the asymmetry of the probability distribution of a real-valued random variable about its Average, and the kurtosis measures the "tailedness" of the probability distribution.

$$Skewness = \frac{n}{(n-1)(n-2)} \sum_{i=1}^{n} \left(\frac{x_i - \mu}{\sigma}\right)^3 \quad (5)$$

$$Kurtosis = \frac{n(n+1)}{(n-1)(n-2)(n-3)} \sum_{i=1}^{n} \left(\frac{x_i - \mu}{\sigma}\right)^4 - \frac{3(n-1)^2}{(n-2)(n-3)} \quad (6)$$

As shown in Table 7, Thumrait has the highest Average wind speed at 5.83 m/s, followed by Masirah (5.50 m/s) and Qairoon Hairiti (5.22 m/s). Raysut has the lowest Average wind speed at 2.34 m/s. The median wind speeds follow a similar pattern, with Thumrait (5.17 m/s), Masirah (5.03 m/s), and Qairoon Hairiti (5.06 m/s). They have the highest values. While Raysut (2.28 m/s) has the lowest. Thumrait exhibits the highest variance (6.60) and standard deviation (2.57).

Table 7: Wind speed data sets descriptive statistics analysis of the selected locations

Selected	Wind speed data analysis at each location					
Location	Average	Median	Variance	Standard deviation	Skewness	Kurtosis
Qalhat	2.82	2.53	1.47	1.21	2.85	9.94
Sur	4.99	4.67	3.15	1.78	0.64	-0.26
Masirah	5.50	5.03	5.06	2.25	0.58	-0.78
Raysut	2.34	2.28	0.63	0.79	2.13	7.75
Marmul	4.33	4.08	1.99	1.41	0.96	1.07
Qairoon Hairiti	5.22	5.06	3.76	1.94	0.97	1.84
Thumrait	5.83	5.17	6.60	2.57	0.91	0.09

This indicates a significant variability in wind speeds. Masirah also shows high variability with a variance of 5.06 and a standard deviation of 2.25. In contrast, Raysut has the lowest variance (0.63) and standard deviation (0.79). This indicates the most consistent wind speeds. Qalhat and Raysut have the highest positive skewness, 2.85 and 2.13 respectively. This indicates distributions with long right tails and more frequent lower wind speeds. Other locations like Masirah and Sur have lower skewness values, 0.58 and 0.64 respectively. This suggests more symmetric wind speed distributions. Qalhat and Raysut have high kurtosis values, 9.94 and 7.75 respectively. This indicates distributions with more extreme outliers (leptokurtic). Sur and Masirah exhibit negative kurtosis, -0.26 and -0.78 respectively. This suggests flatter distributions with fewer extreme values (platykurtic).

4.2 Wind direction variation

Wind direction variation refers to the fluctuations in the compass direction from which the wind blows over a specified period. These variations reflect the need for a modern wind turbine system that has good yaw and pitch-angle controls. Figures 12 to 18 show the wind direction variations during 2023, for the selected locations, respectively.

As shown in Figures 12 to 18, Qalhat experienced winds primarily towards the north to northwest directions. It is indicating a northerly pattern with slight variations towards the west. Sur encountered winds predominantly from the south to southwest directions, with occasional shifts towards the west. Masirah observed a combination of wind directions, ranging from south to southwest directions, with chance shifts towards the east. Wind directions altered and represented a wide range of variability. Raysut experienced winds primarily towards the south direction, with fluctuations between southeast and southwest directions. Marmul observed wide-range winds towards the southeast direction, with occasional shifts towards the east and south. Qairoon Hairiti experienced winds predominantly towards the south-to-southeast direction. Thumrait experienced a range of southerly winds with variations towards the southeast.

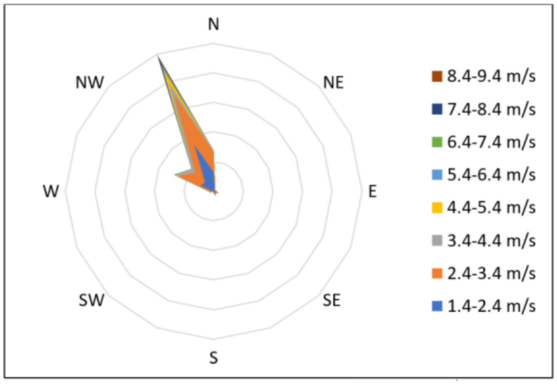

Figure 12: Wind direction variations at Qalhat location

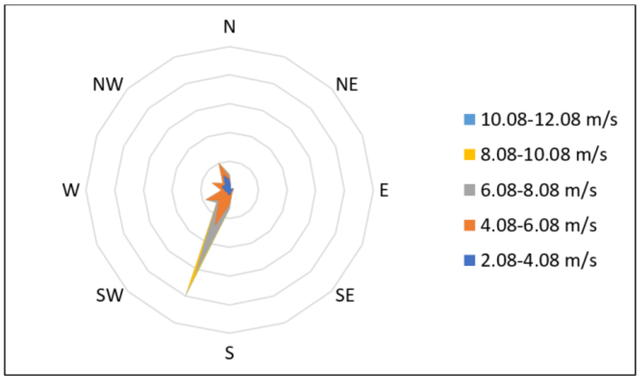

Figure 13: Wind direction variations at Sur location

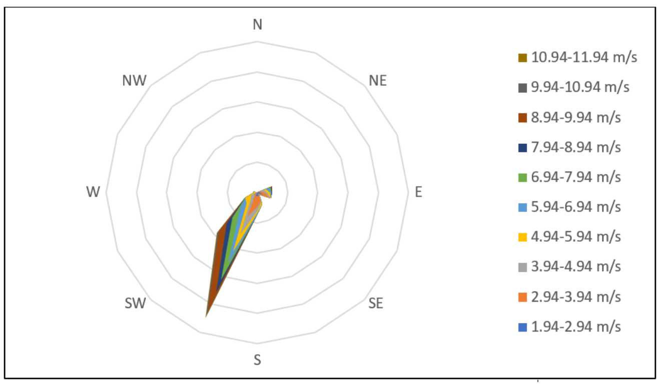

Figure 14: Wind direction variations at Masirah location

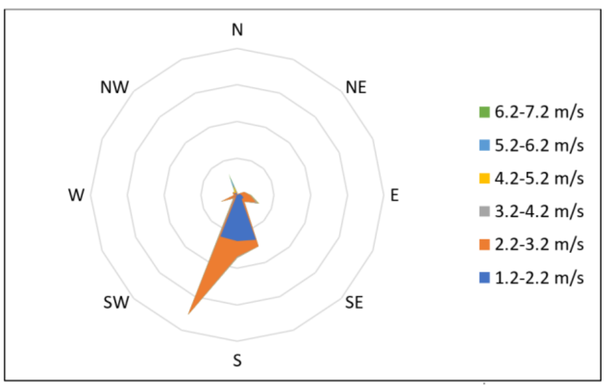

Figure 15: Wind direction variations at Raysut location

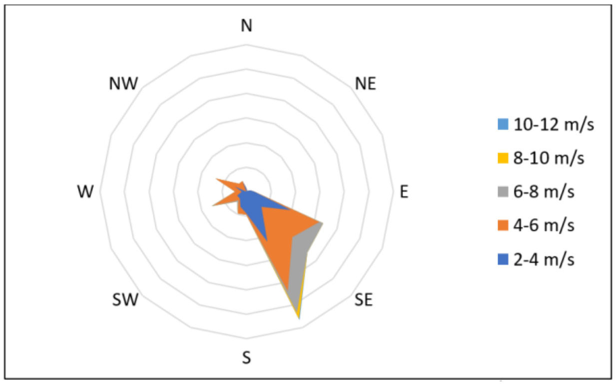

Figure 16: Wind direction variations at Marmul location

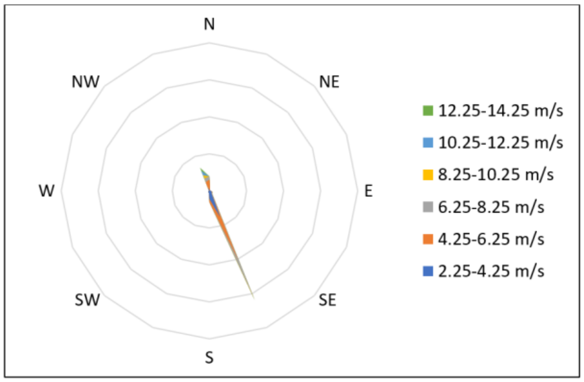

Figure 17: Wind direction variations at Qairoon Hairiti location

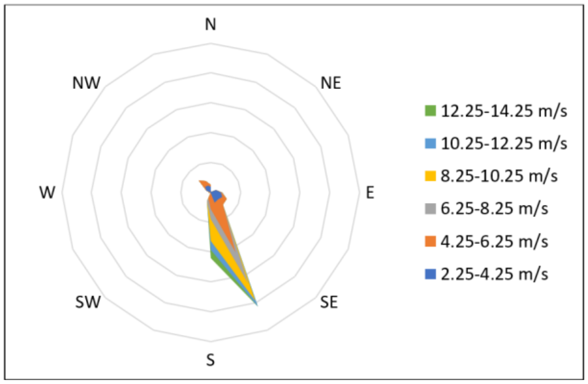

Figure 18: Wind direction variations at Thumrait location

Wind direction variations can impact the wind power generation in several ways:

- Efficiency: Wind turbines are designed to face the wind to capture the maximum amount of energy. When the wind direction changes, the turbine's yaw control mechanism must adjust to realign the turbine system with the wind. Frequent changes in wind direction can cause inefficiencies as the turbine spends time adjusting rather than generating power.
- Turbulence: Variable wind directions can lead to increased turbulence. This can reduce the efficiency of the turbine blades and cause wear and tear on the mechanical components. Turbulence can also lead to less consistent energy production.
- Optimal positioning: Wind farms are usually sited based on prevailing wind directions. The aim is to maximize energy capture. If the actual wind direction varies significantly from the expected patterns, then the positioning of turbines may not be optimal. This will reduce the overall energy output.

- Wake effects: In a wind farm, turbines create wake effects that impact downstream turbines. The variations in wind direction can change these wake patterns. This will potentially reduce the efficiency of turbines that are downwind.
- Load variability: Changing wind directions causes changing loads on turbine components. This can lead to increased maintenance requirements and shorter lifespans for the turbines.

To mitigate these issues, wind farms need to use advanced forecasting techniques and real-time monitoring systems. These techniques predict and respond to changes in wind direction, optimize the turbine performance and maintain consistent power generation.

4.3 Predicted Power Output

Wind turbine generation involves the conversion of kinetic energy from wind into electrical energy. The aerodynamic power P_{aero} extracted from the wind is given by:

$$P_{aero} = \frac{1}{2}\rho A v^3 C_p(\lambda, \beta) \tag{7}$$

where ρ is the air density (kg/m³), A is the swept area of the turbine blades (m²), v is the wind speed (m/s), $Cp\ (\lambda, \beta)$ is the power coefficient, which is a function of the tip speed ratio λ and the blade pitch angle β. The tip speed ratio λ is defined as:

$$\lambda = \frac{\omega R}{v} \tag{8}$$

where ω is the angular velocity of the rotor (rad/s) and R is the radius of the turbine blades (m).

Incorporating the Betz coefficient, it is dictated that no turbine can capture more than 59.3% of the kinetic energy in the wind (0.593 represents the Betz coefficient or Betz's limit). The Betz coefficient is needed for determining the upper bounds of turbine performance and ensuring that our predictions remain within feasible parameters:

$$P_{max} = 0.593 \times \frac{1}{2}\ \rho A v^3 \tag{9}$$

The actual power output (P_{actual}) can be further refined by incorporating the turbine's power coefficient (Cp), which typically ranges between 0.3 and 0.5 for modern wind turbines:

$$P_{actual} = C_p \times 0.593 \times \frac{1}{2}\ \rho A v^3 \tag{10}$$

The predicted theoretical power generation potential was assessed across seven locations: Qalhat, Sur, Masirah, Raysut, Marmul, Qairoon Hairiti, and Thumrait. These calculations were then compared with the actual performance data from the GE 3.8 MW wind turbine system installed at the Dhofar wind farm in Oman. The goal is to evaluate the feasibility and viability of renewable energy projects in these locations based on the existing wind turbines installed in Dhofar wind farm. Figure 19 shows the comparative discussion of the selected locations, namely; Qalhat, Sur, Masirah, Raysut, Marmul, Qairoon Hairiti, and Thumrait.

As shown in Figure 19, Qalhat and Raysut, with average wind speeds of 2.82 m/s and 2.34 m/s respectively, exhibit the lowest predicted wind power (182.32 kW and 104.17 kW) and actual power outputs (43.25 kW and 24.71 kW). This low performance was consistent with their minimal wind speeds. Conversely, Thumrait, with the highest average wind speed of 5.83 m/s, achieved the highest predicted wind power of 1610.97 kW and an actual output of 382.12 kW. This illustrated the significant impact of higher wind speeds on power generation potential. Mid-range locations like Sur, Masirah, and Qairoon Hairiti, with wind speeds between 4.99 m/s and 5.5 m/s, displayed predicted power outputs ranging from 1010.14 kW to 1352.60 kW, and actual outputs from 239.61 kW to 320.84 kW. Marmul, with a wind speed of 4.33 m/s, has a lower predicted power of 660.00 kW and an actual output of 156.55 kW. The Betz adjusted power, reflecting the theoretical maximum efficiency (59.3%), consistently showed higher values than the actual outputs due to real-world inefficiencies such as mechanical and aerodynamic losses. This pattern was evident as the actual power outputs across all locations were roughly 24% of the predicted values. This indicated a significant drop due to practical limitations in turbine performance. Higher wind speeds correlated with higher predicted and actual power outputs.

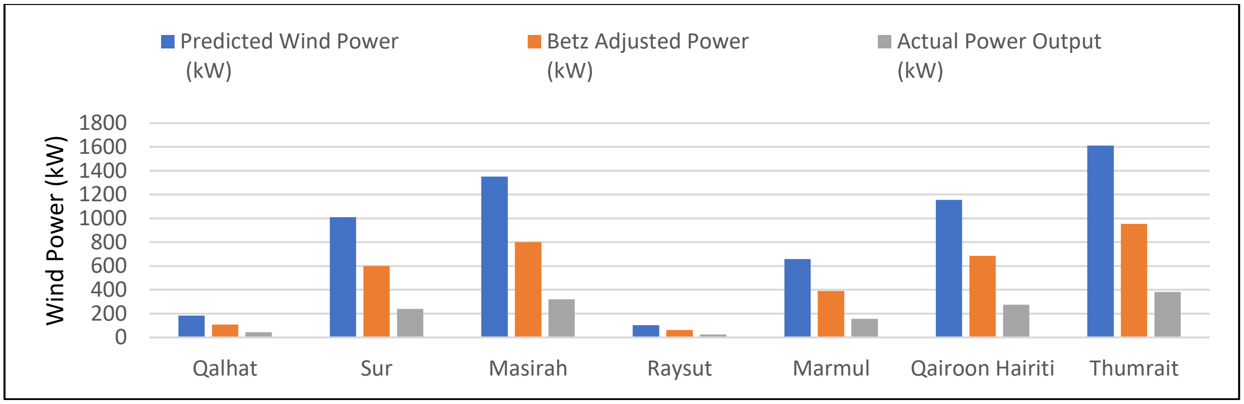

Figure 19: Predicted, Betz Adjusted and Actual Power in Locations

5. Conclusion

In conclusion, this study evaluated the wind power potential across seven selected locations in Oman (Qalhat, Sur, Masirah, Raysut, Marmul, Qairoon Hairiti and Thumrait). The data sets from these seven meteorological stations were used to analyze wind speed and direction variations in 2023. The results revealed significant geographical variations (coastal or inland). Coastal locations like Sur and Masirah demonstrated high wind power potential, while inland locations such as Thumrait show even higher potential. Conversely, locations like Qalhat and Raysut exhibited lower wind power capabilities due to their lower average wind speeds. This comparative analysis underscored the importance of considering both theoretical potential and practical inefficiencies in wind power generation planning in Oman, and highlighted the varying performance based on location-specific wind conditions.

Despite the comprehensive analysis, the study faced some limitations. The data sets were of a single year's data. If similarly detailed data sets for the past decade were gathered, then a much clearer analysis would be performed. Also, the exclusive use of the GE 3.8 MW turbine model in Oman might not be optimal for all locations. Additionally, real-world inefficiencies, such as mechanical and aerodynamic losses, were found to reduce the actual power output compared to theoretical predictions.

The findings have important implications for future research, policy and intervention. Future research should incorporate multi-year data sets and explore new turbine models to optimize wind power generation across varied locations. Policymakers should consider these findings to strategically plan and develop wind farms, and focus on high-potential areas to maximize energy output. Interventions should also include investments in advanced forecasting and monitoring systems to enhance turbine efficiency and durability, ensuring clean, sustainable and reliable wind energy production in Oman.

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