Embedded Selforganizing Systems

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Feasibility of Offshore Wind Energy in Northern United Arab Emirates: Diurnal Wind Dynamics and Turbine Power Curve Analysis.

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***Abstract*-The United Arab Emirates (UAE) has been actively involved in organising and working on contributing towards achieving the decisions made at the COP28. The main aim has been exploring the options for a renewable energy mix. This study investigates the feasibility of offshore wind energy in the northern emirates of the UAE by analysing diurnal wind patterns, wind resource characterization, Weibull distribution curves, wind power density, and Wind turbine power curves across selected offshore locations in the emirate of Sharjah, Ajman, Umm Al Quwain, and Ras Al Khaimah using long 12 plus years of wind data (2012 to 2024 April). Exploratory statistical analyses, such as wind rose, and Weibull distribution estimations, provided critical results for sustainable wind energy planning and development. The performance of four different wind turbines is valuated at these locations, analysing their wind power output over a 24-hour period. These findings, directly affect the design and operation of wind energy systems and contribute to understand the wind energy dynamics and turbine behavior, which will lay the foundation for optimising and sustainable development of Offshore wind energy systems in the northern emirates of UAE. The practical implications of this study highlight its potential to assist in decision-making processes for the government, invite the investors and further facilitate the development of sustainable energy solutions in the region, and invite academic communities to do further research on economic feasibility for the sustainable wind power development aligning with the UAE's efforts to achieve renewable energy targets and mitigate climate change.**

Keywords: Offshore wind energy, United Arab Emirates, diurnal wind patterns, turbine performance, renewable energy, floating wind turbines, wind resource assessment, Sustainable development, Wind Resource Assessment

I. INTRODUCTION & BACKGROUND

The aim of the UAE is to achieve the targets decided during the COP28 agreement by exploring renewable energy options to reduce carbon emissions and meet the rising sustainable demand. Even though wind power has been a sustainable alternative, its sustainable harnessing needs a deep understanding of local wind characteristics and turbine performance [1]. The UAE is dynamically exploring sustainable energy solutions to meet its growing energy demands and meeting its environmental concerns [2].

This study evaluates the feasibility of offshore wind energy in the northern emirates of the UAE by analysing the variations in diurnal wind speed, characterization of wind resources, analysis of Weibull Distribution and investigation of Wind Power Density and through study of Power Output Profile of Selected wind turbines for the offshore locations of the emirate of Sharjah, Ajman, Umm Al Quwain, and Ras Al Khaimah (Northern emirates).

The UAE's energy policy intends to add the share of clean energy to its total energy mix from 25% to 50% by 2050 [3]. Today, the UAE has not installed wind turbines in its Offshore waters. However, the UAE has been investing seriously in other renewable energy technologies, such as solar and onshore wind installations, to achieve its sustainability objectives [4]. There are abundant studies available on solar energy research and its installations in the UAE, but the opportunity and feasibility of wind energy development have not been researched and explored widely. The analysis of previous studies shows only very few studies on wind energy, and that too on its macro levels of development and the research on micro-level wind power

developments, such as site-specific wind resource assessments, and the characteristics of wind variations and its relationship with changing climates are negligible and the research gap is huge. For example, according to [5], a study on the feasibility and availability of sustainable wind energy in the UAE is highly needed, as the UAE has been at the forefront of promoting and transitioning towards interdisciplinary renewable energy sources. The investigations on wind power development options and investing in wind power development are very crucial as the UAE is interested in elaborating its investments and developing job opportunities in the power sector [6]

The result of this study significantly fills the current research gap in the wind energy studies of the Northern emirates of AUE and opens the gaps to further expand the research to other parts of UAE, by giving in-depth knowledge about diurnal wind speed variations, characterization of wind resources, analysis of Weibull Distribution and investigation of Wind Power Density and thorough investigation of Power Output Profile of Selected wind turbines spreading throughout the Northern emirates of UAE (Emirate of Sharjah, Ajman, Umm Al Quwain, and Ras Al Khaimah). This study greatly supports the UAE's goals to achieve renewable energy targets and mitigate the impacts of climate change. This study will also motivate the government and wind energy investors to explore further in detail by providing necessary support in researching wind power installation options in UAE waters.

Figure 1. Study location: Offshore of Northern Emirate of UAE

II. Objectives of the Study

This research study aims to assess the possibility and feasibility of installing offshore floating wind turbines in the northern emirate of UAE. The study will achieve the following objectives:

1. Analyze variations in diurnal wind patterns across four selected offshore locations (20km away from the shore) in the emirate of Sharjah, Ajman, Umm Al Quwain, and Ras Al Khaimah.
2. Evaluate wind power density to determine the potential for energy generation and optimise wind farm design.
3. Investigate the performance of three different wind turbine models, Aeronautica 47-750 MW, Avantis AV 928-2.5MW, Gamesa G114-2.5 MW and Gamesa 136-4.5MW under various wind conditions.
4. Provide valuable insights into wind energy dynamics and turbine behavior in the UAE to inform decision-making processes and facilitate the development of sustainable energy solutions in the region.
5. Identify the challenges and opportunities associated with offshore wind energy projects and contribute to advancing renewable energy planning and infrastructure development in the UAE.
6. Align the study's findings and implications with the UAE's efforts to achieve renewable energy targets, reduce carbon emissions, and mitigate climate change in accordance with the COP28 agreement.

By addressing the above objectives, this study aims to explore and provide a comprehensive assessment of the feasibility of offshore wind energy in the offshore waters of the northern emirates of the UAE. It will lay the foundation for informed decision-making and strategic planning in the renewable energy sector. The findings of this research will contribute to the UAE's ongoing efforts to expand its energy mix, reduce its dependence on fossil fuels, and promote sustainable development in the region.

III. Literature Review

Previous studies, such as [7] have explored the requirements for policies for developing wind power in the UAE and discussed the challenges associated with its implementation. They identified that investment challenges, environmental impacts of wind farm developments, difficulties in power transmissions and associated infrastructure developments and limitations of public awareness on wind energy installations have been identified as the constraints for wind energy harnessing and development, but since then, wind power technology has been developed tremendously, especially the developments in low wind speed turbine technologies and floating wind turbine technology development made these constraints negligible.

A recent study by [8] using GIS, the study found that the UAE's area suitable for onshore wind energy installation is limited to just 11% of the total area. The above study also pointed out that, in light of recent developments in wind energy technologies, there is abundant potential for Offshore wind power development along the exclusive economic zone of the UAE. A study by [9] stated the huge opportunity for the development of urban building-based wind turbine installations, especially in the emirate of Ajman.

[10] Also, their study, using a questionnaire survey, indicated that factors such as technological innovations, environmental impacts, socioeconomic aspects, and difficulties in grid integration are the constraints in wind energy adoption in the UAE. [11] in their study on overview of wind resource assessment focusing on the emirate of

Ajman, they discussed the importance of site-specific wind resource assessment by pointing out the importance and biases in the wind data sources. The study highlighted how the wind data from widely used sources differ. The study analysed and emphasised how the environmental characteristics and site-specific climatic variables are important while doing wind resource assessment, especially the importance of site-specific wind data at the hub height of wind turbines.

An economic feasibility study by[12] on offshore wind power in UAE, the study found that there is a very high probability of installing floating wind turbines Offshore of Abu Dhabi, however the result of an earlier study by [13] has pointed out through a GIS study that, due to the sensitive receptors present in the major parts of the Ab Dhabi waters, Delma Island and North of Barakah in the western region are only suitable for offshore wind turbine installations. And [14] made a critical review of the possibility of producing hydrogen fuel using offshore wind energy since offshore wind turbines have a higher capacity factor than their onshore counterparts. [15] studied the feasibility of installing offshore wind turbines in Abu Dhabi waters by mimicking a study on a wind farm installed in Friesland, Netherlands. They found that since the region has a wind speed greater than 5.4m/s, a 600 MW wind farm can be developed using a Vestas wind turbine (V90), producing 1.1778 TWh of gross wind power annually.

As discussed above, the literature review on wind energy studies specifically focusing on the UAE has done macro-level investigations and explorations of wind power development opportunities in the offshore waters of the UAE. Past studies have shown both challenges and opportunities involved while developing and installing wind energy systems in the UAE

In conclusion, there is a huge need for further micro-level, site-specific studies and research on Offshore wind power developments in the UAE, considering the research gaps, challenges and opportunities in the UAE. Hence, this study aims to fill the gaps in offshore wind resource and wind energy studies, especially focusing on the Northern Emirates (Emirate of Sharjah, Ajman, Umm Al Quwain, and Ras Al Khaimah) of UAE by filling the gaps specifically considering analysing the variations in diurnal wind speed, characterization of wind resources, analysis of Weibull Distribution and investigation of Wind Power Density and through the study of Power Output Profile of Selected wind turbines for the aforementioned offshore locations.

IV. METHODOLOGY

This study employed state-of-the-art Windographer 5[16] software from AWS. The software was used to analyse wind data and perform statistical and wind energy-related analyses to meet the objectives of this study. The wind data monitored at a height of 50 meters from sea level was collected from the NASA satellite during the period from 2012 to April 2024 at four selected Offshore locations (20km away from the shore) of Northern Emirates (Emirate of Sharjah, Ajman, Umm Al Quwain, and Ras Al Khaimah) was used for this study. The wind data was used to plot the variations in diurnal wind speed and wind roses and study the wind speed magnitude and predominant wind direction from offshore locations of the emirates. The data was then used to plot wind speed distribution and estimate Weibull distribution parameters such as shape parameter K and scale parameter C for all the selected locations. Then, the wind data was used to estimate and study the wind power density and the power out profile of effective wind turbines such as Aeronautica 47-750 MW, Avantis AV 928-2.5MW, Gamesa G114-2.5 MW and Gamesa 136-4.5MW.

V. RESULTS AND DISCUSSION

A. Diurnal and Monthly Wind Speed Variation Analysis:

Figure 2 below shows the 30-day moving average wind speed at 50 m height at the northern emirate of UAE. The analysis of Figure 2 indicates that Ras Al Khaimah shows the highest consistent wind speed variability with peaks exceeding 12 m/s, especially from 2015 to 2017. [17] also made the same observation. The study explains that northern coastal regions of the UAE show very good seasonal wind speed fluctuations due to the region's unique climatic conditions, implying the necessity for site-specific wind resource assessment.

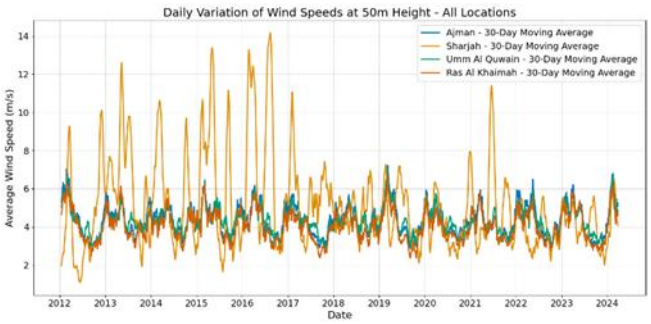

Figure 2.Diurnal Variation of Wind Speeds at 50m Heigh at Offshore locations of Northern Emirates of UAE (2012-April 2024).

However, the analysis of Figure 2 also explains that the emirate of Ajman shows the least variations in wind speed, which averages between 2 and 5 m/s. The emirate of Sharjah and Umm Al Quwain shows moderate wind speed, which indicates medium wind potential, and this is similar to the findings of the study by [18] who also pointed out that coastal regions of the UAE show consistent wind speed variations and are, hence, suitable for steady wind energy production.

Figure 3 below depicts the monthly variations of wind speed at 50m heights offshore of the northern emirates of UAE from 2012 to April 2024, and the figure clearly strengthens the results shown by the diurnal variation plot in **Figure *2***. The analysis of Figure *2* reveals that Ras Al Khaimah showed the highest mean wind speed with a peak value of 6 m/s from February and March, which declines towards the middle of the year. The analysis of **Figure *3*** reveals that the emirate of Ajman shows a comparatively stable wind speed profile throughout the year, with mean wind speed varying from 3 to 4.5m/s. The monthly wind speed variations in the emirate of Sharjah and Umm Al Quwain are observed between 4 and 5.5m/s during the first months of the year, and they start to decline to 3 m/s in later months, and this shows the possibility for a balanced wind energy production.

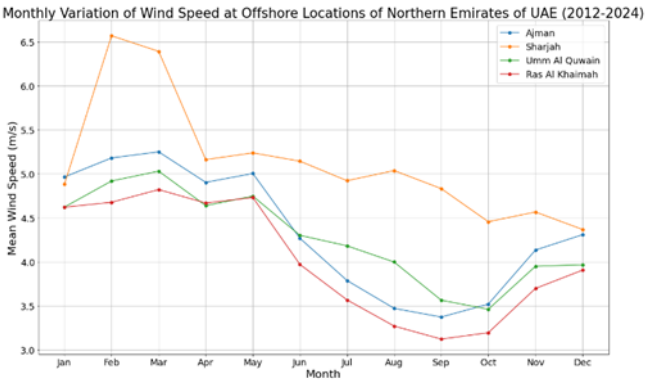

Figure 3. Monthly Variation of Wind Speed at the 50-meter height at Offshore Locations of Northern Emirates of UAE (2012-April 2024)]

The analysis of the above figures clearly shows the importance, criticality, and necessity of a site-specific, tailored approach for obtaining offshore wind power in the UAE. Moreover, understanding and researching the emirate-specific wind dynamics and strategy for wind energy development is also necessary.

The above result, unlike other previous studies such as [7], [19],[18],[10] who emphasised the feasibility of wind energy development in the UAE qualitatively and broadly using short-term wind data. This present study result, supported by the analysis of 12 long years of temporal wind data at the offshore locations of the northern emirates of UAE, clearly shows the potential for wind energy development in the UAE, especially floating offshore wind turbines, and strengthens the wind energy assessment and fills the gaps in previous studies. The analysis result of this study can especially be used for wind turbine and wind farm designs. The study also gives detailed implications and understanding of how shamal winds and changes in climatic patterns affect wind potential, which was never analysed in past research in the region. The output of this study can be practically utilized to align wind turbines/wind farms to obtain maximum wind energy. Academically, this study set an example for comprehensive wind data analysis that can be followed globally.

B. *Wind Resource Characterization of Northern Emirates:*

This section analyses the wind resources using wind rose plots at 50m height at four offshore locations of the northern emirates of the UAE (Sharjah, Ajman, Umm Al Quwain, and Ras Al Khaimah) using wind data from 2012 to 2024 April. The wind rose plot gives the magnitude and direction distribution of wind speed at any location. Analysing the wind rose plots at the above offshore locations gives deep insights into planning sustainable wind power projects in the northern emirates of UAE.

- *Wind Resource Characterization in the Emirate of Sharjah:*

Figure 4 below shows the wind rose plot at 50m height for the Offshore location of the emirate of Sharjah. The analysis of the figure reveals that at the location, the predominant winds are from the West (W) and West-Northwest (WNW) directions. That accounts for approximately 55-65% of the total winds. The wind speed observed ranges from 5-10m/s, with fewer occurrences of higher wind speeds between 10-15m/s. This long-term (2012 to April 2024) wind data analysis shows that there are steady, moderate winds coming from consistent wind directions, which shows the viability of an offshore wind project offshore of Sharjah, and this result aligns with the previous studies by [20][19]

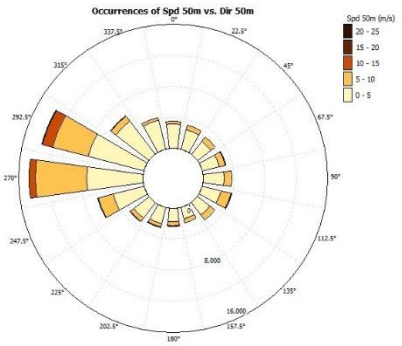

Figure 4. Wind Rose for Offshore of Sharjah (2012-April 2024)

- *Wind Resource Characterization in the Emirate of Ajman:*

For offshore Ajman, as seen in the wind rose plot for the period (2012 to April 2024), which is as shown in Figure 5, the prevailing wind direction is from the West (W) with significant occurrences from the northwest (WNW), direction. The predominant wind speed ranges between 0-5m/s and 5-10m/s. This observed wind speed is consistent with the wind regime discussed in the study of [19], who explains how important consistent wind conditions are for generating sustainable wind energy. Therefore, aligning the turbine's WNW can increase wind energy efficiency at this location, as [18] suggested. This long-term wind data analysis from offshore Ajman shows that wind conditions at 50m height at offshore of the emirate of Ajman are suitable for continuous wind power generation.

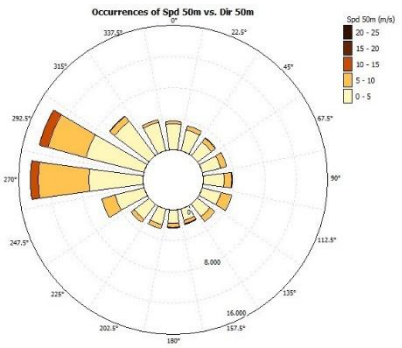

Figure 5. Wind Rose for Offshore of Ajman (2012-April 2024)

- *Wind Resource Characterization in the Emirate of Umm Al Quwain:*

Figure 6 below explains the wind rose plot at 50m height offshore of Umm Al Quwain. The figure shows that the prevailing wind direction is from the west (W), with significant occurrences from the west-northwest (WNW).

The analysis of the rose plot shows that wind speed is mainly distributed between 0-5m/s and 5-10m/s. The analysis of this long 12 years of wind data reveals the consistency and steadiness in the wind speed at this offshore location, clearly indicating the feasibility of developing a sustainable offshore floating wind farm. which reinforces the findings by [10] on the need for consistent wind conditions for wind energy projects in UAE coastal waters.

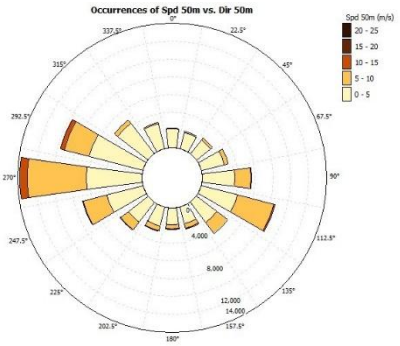

Figure 6. Wind Rose for Offshore of Umm Al Quwain (2012- April 2024)

The analysis of Figure *6* shows that the West (W) direction is the dominant and primary wind direction with crucial occurrences from west-north (WNW). The wind speed values range from 0-5m/s and 5-10m/s, implying consistent, reliable wind resources ideal for sustainable wind power development. This wind resource condition analysed using a wind rose plot using 12 long years of wind data shows a sustainable, robust view of the wind regime in the area, which aligns with a recent qualitative study in the region by [10]

- *Wind Resource Characterization in the Emirate of Ras Al Khaimah:*

Figure *7* below depicts the wind rose plot explaining the magnitude and direction distribution of wind speed offshore of the emirate of Ras Al Khaimah from April 2012 to April 2024. The analysis of the rose plot shows that the predominant wind direction is from the west (W), and the dominant wind direction is from the west-southwest (WSW). The wind speed values ranged from 0-5m/s and 5-10m/s, which is consistent with other emirates analysed above. This consistency, steadiness, and stability in wind direction, as seen using this long-term wind data, implies an opportunity for a Robust turbine design and wind farm development along the northern emirate. This result aligns with the findings of [20].

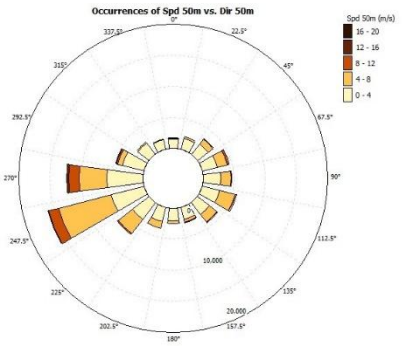

Figure 7. Wind Rose for Ras Al Khaimah (2012- April 2024)

C. Comparative Analysis and Key Findings

The comparative analysis of all the windrose plots at various offshore locations in the northern emirates clearly shows that there is consistent, stable coherence of predominant wind directions from West (W) and West North West (WNW), with Ras Al Khaimah showing occurrences from West South West direction. This constancy in predominant wind direction is critical information in wind turbine designs and wind farm layout optimization. This present study using wind data from 2012 to 2024 April gives more in-depth information and deep variation about the wind resource characteristics of northern emirates, which is lacking in previous studies like [7],[19] [10] Therefore, this study significantly contributes to the decision-making process by the government and investors and further research opportunities for academic communities alike, filling a huge gap in the literature. Hence, this comparative analysis helps plan, optimise, and install wind energy systems to achieve the UAE's COP28 goals.

D. Weibull Distribution Estimation:

This section analyses the Weibull distribution curves of various offshore locations in the Northern Emirates (Sharjah, Ajman, Umm Al Quwain, and Ras Al Khaimah). Figure 8 below shows the Weibull Distribution Curve at 50m height for the Offshore of Sharjah. The Weibull curve analysis explains that most wind speed falls between 3 and 7.5m/s, indicating a moderate wind pattern with a Weibull Shape parameter (K) value of 1.81 and a Weibull Scale Parameter (K) value of 5.80m/s.

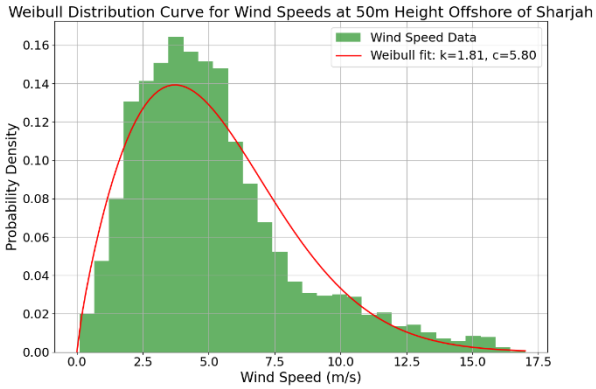

Figure 8. Weibull Distribution Curve for Offshore of Sharjah (2012- April 2024)

Since the value of "K" is less than 2, it means that there is a mix of wind speeds with various ranges having variable wind conditions. When comparing this study's result using long-term data (12 plus years) with previous studies, it is concluded that the result is in conformance with the previous short study by [20], which explains the location's moderate wind speed, which is suitable for wind turbine installations.

Figure 9 below depicts the Weibull distribution curve offshore of Ajman, with Shape parameter (K) 2.29 and Scale parameter (C) 4.94 m/s. the shape parameter value of 2.29 shows that the wind speed is more stable and favourable for steady wind energy generation than the emirate of Sharjah. However, this stability in wind speeds supports the feasibility of offshore wind energy projects, as [19] suggested. The scale parameter value of 4.94m/s indicates a low wind speed characteristic, so it may not be best for high wind energy production. However, with proper planning, maximum wind power can be extracted by choosing the best available wind turbine from the current market from highly developed sophisticated turbine manufacturers or by designing a suitable site-specific turbine using these long-term data analysis results. However, an economic analysis shall be conducted in the future to see a return on investment using the results of this study.

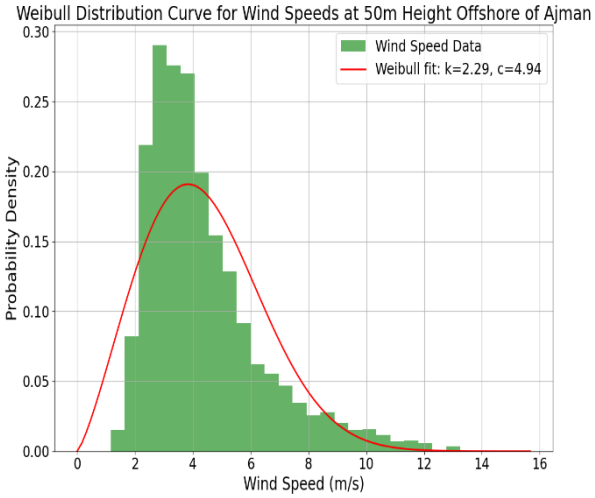

Figure 9. Weibull Distribution Curve for Offshore of Ajman (2012- April 2024)

Figure 10 below explains the Weibull distribution curve at the Offshore of Umm Al Quwain, with Shape parameter (K) 2.47 and Scale parameter (C) 4.84 m/s from 2012 to April 2024.

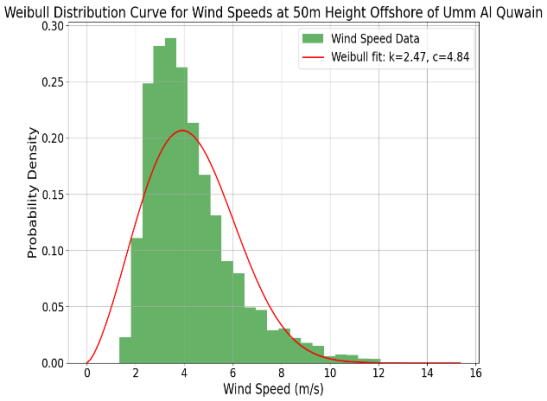

Figure 10. Weibull Distribution Curve for Offshore of Umm Al Quwain (2012- April 2024)

The shape parameter (K) value 2.47 at the location indicates the narrow distribution of wind speed, which means a steady, less variable wind resource. However, as seen above, the location has a scale parameter value of 4.84m/s, which shows a low characteristic average wind speed. However, the high K value seen above gives a steady capacity factor. Given the availability of good capacity factors with the selection of wind turbines for low wind speed regions, energy production will not be an issue as there is steady wind speed at the location.

Figure 11 below shows the Weibull distribution curve at Offshore of Ras Al Khaimah with Shape parameter (K) 2.21 and Scale parameter (C) 4.57 m/s from 2012 to April 2024.

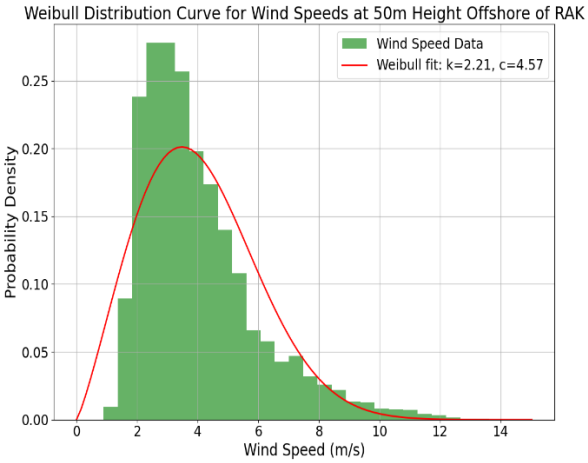

Figure 11. Weibull Distribution Curve for Offshore of Ras Al Khaimah (2012- April 2024)

The shape parameter (k) of 2.21 indicates only moderate consistency in wind speed with little variability. Similar to the offshore of Umm Al Quwain, this location also needs a specially designed wind turbine for optimum energy production. This study using long-term wind data extends the similar study by Jamil et al. (2016), which also pointed out the necessity for specially designed turbines for this location.

- Comparative Analysis of Weibull Distribution Curves at Northern Emirates (2012- April 2024):

Analysis of the Weibull distribution parameters derived using long-term wind data (2012-2024 April) at 50m height Offshore of studied locations in the Northern Emirates provided details on the prevailing wind characteristics and background information about the wind turbine types that must be used for maximum energy yield at each offshore locations of northern emirates. The result of this study using long-term wind data (12 plus years) at chosen offshore locations, especially the emirate of Sharjah, Ajman and Umm al Quwain, aligns with observations and is in good agreement with the result of the previous study by [20],[19].

This reliability in wind characteristics and wind speeds is very important for the economic operation of wind turbines and sustainable energy production. On the other hand, the offshore location of the emirate of Ras Al Khaimah showed slightly increased variable wind speeds, which demands the implementation of specially designed advanced turbine technologies to capture wind energy efficiently. As per the study, [10] also, the crucial requirements for specially designed wind turbines for this kind of area where less stable wind conditions prevail. The study explains the various factors that are influencing and impacting the implementation of wind power in the UAE. The result of the comparative analysis is of utmost importance while installing, selecting site-specific wind turbines, and optimising wind farm layouts for the offshore locations of each emirate. Above all, this study fills a huge gap in the literature, which will also help sustainable Offshore wind energy planning in the northern emirates of UAE, each emirate, wind energy investors, and wind energy researchers.

E. *Analysis of Wind Power Density:*

The 30-day rolling average Wind Power Density (WPD) at 50m height Offshore in the emirates of Sharjah, Ajman, Umm Al Quwain, and Ras Al Khaimah has been analysed from 2012 to April 2024. **Figure 12** shows the variation of WPD at 50m height at all the offshore locations of the northern emirates.

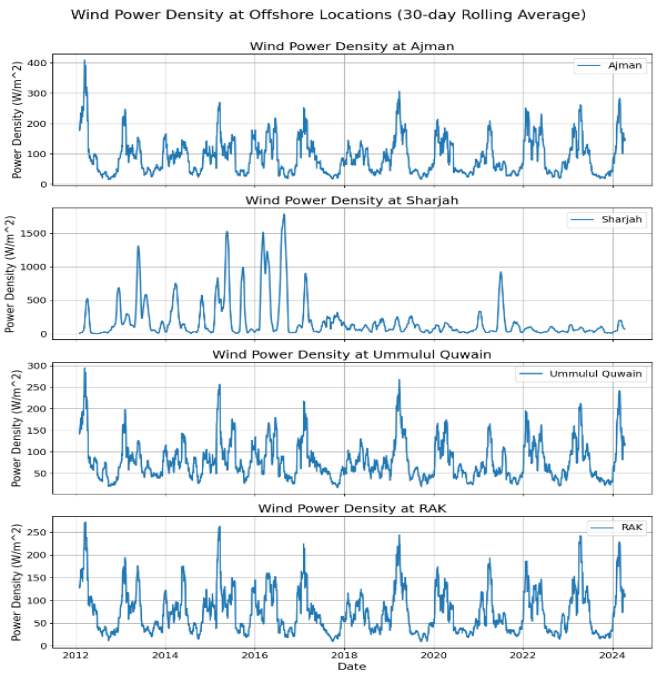

Figure 12. Wind Power Density Plot for Offshore of Northern Emirates UAE (2012- April 2024).

The analysis of Figure 12 reveals that Sharjah's wind power density sometimes exceeded the WPD value of 1500W/m^2. All other locations showed distinct WPD values. The high events in the plot show the presence of climatic Shamal winds. This finding supports Gherboudj (2024), who stressed harnessing high-energy wind events to optimise wind power generation.

The emirates of Ajman and Umm Al Quwain exhibited steady WPD values, with a peak of less than 500 W/m2. However, compared with Sharjah, they have less total energy potential. The steady WPD shown above is consistent with the recommendations made by [19],[10], who pointed out that there is a need for stable and moderate wind to ensure dependable energy production. Hence, this study, with 12 plus years of wind data (2012 to April 2024), gives a deep understanding of the wind potential, which conforms to the suitability of the above sites for developing sustainable offshore wind farms through the development of specially designed wind turbines to harness this wind energy completely. Also, as seen offshore of Umm Al Quwain & in the emirate of Ajman, the consistent and stable wind regime is suitable for installing newly developed advanced wind power systems for continuous energy development. The high temporal variability in WPD offshore of Sharjah and Ras Al Khaimah clearly shows the influence of global climatic events like El Niño and La Niña in the wind speed of the northern emirates of UAE, which should be further investigated in future studies and how this will affect the wind turbine operations and energy production in Northern emirates of UAE.

TABLE 1 below summarises the comparative analysis of the wind characteristics offshore of the northern emirates. Among all the emirates, Sharjah exhibited the highest average wind speed value and WPD values of 5.14 m/s and

186.69 W/m², respectively, indicating its potential for wind power generation compared to other emirates.

TABLE 1. COMPARATIVE ANALYSIS OF THE WIND CHARACTERISTICS OFFSHORE OF THE NORTHERN EMIRATES

Location	Av, WS (m/s)	WPD (W/m²)	Weibull k Value	Weibull C (m/s)	Prevailing WD	High WS (13-20 m/s)
Sharjah	5.14	186.69	1.81	5.80	West	2.45 %
Ajman	4.36	90.54	2.29	4.94	West	0.16 %
Umm Al Quwain	4.29	79.31	2.47	4.84	West	0.04 %
Ras Al Khaimah	4.03	74.13	2.21	4.57	Southwest	0.07 %

F. comparative analysis of wind characteristics

The Weibull K value of 1.81 offshore of Sharjah shows increased variability in wind speed distribution, and the emirate also observed higher frequency (2.45%) for the highest wind speeds from 13-20m/s, further reinforcing suitability for wind power development project. Other emirates, Ajman, Umm Al Quwain, and Ras Al Khaimah even though showed comparatively reduced wind speed values (4.03-4.35m/s) and WPD values (74.13- 90.54 W/m²), but these locations have Weibull K parameters from 2.21 to 2.47 which indicates a reliable wind speed distribution and its very good for stable wind energy generation. The analysis of TABLE 1 shows that the predominant wind direction for all the emirates is from the West, but Ras Al Khaimah experiences it from the southwest direction. The frequency of occurrence of higher wind speed is at the offshore of Sharjah (0.04% to 0.16%) compared to other emirates. Among all the analysed offshore locations in the Northern Emirates of UAE, offshore Sharjah is the most suitable location for an individual wind turbine and wind farm development since offshore Sharjah showed higher average wind speed value, WPD and frequency of higher wind speed. Among other studied offshore locations, the offshore emirate of Ajman is the second most suitable location for stable wind power installation and location for energy generation as the emirate of Ajman showed higher WPD than Umm Al Quwain and Ras Al Khaimah. In conclusion, the analysis also implies and recommends that there is a high possibility for the installation of a combined optimum power-generating wind farm combining all the emirate that will give a stable, reliable, consistent and sustainable wind power generating system

Past studies, such as [10]. had only provided a general overview of wind resources, this study gives a specific detailed understanding of the wind regimes in the northern Emirates. This study fills this huge gap by contributing the results by analysing long-term data from 2012 to April 2024 and extending the temporal scope of the preceding research. This study provides a long-term understanding of how WPD changes and varies along northern emirates. Therefore, it will help design specific wind power development strategies in the offshore northern emirates of the UAE. With Sharjah having shown peak WPD values, it can contribute to total wind power output. But Ras Al Khaimah, with its variable WPD, requires very careful site selection when optimising wind turbine systems. However, the offshore emirate of Ajman and Umm Al Quwain, as seen in their stable WPD, gives promises to harness sustainable wind power production.

G. Analysis of Power Output Profiles of Selected Wind Turbines:

The power-output profiles of selected wind turbines at offshore locations of the northern Emirates of UAE have been studied. The analysis compares the suitability of selected wind turbine models (Aeronautica 47-750 MW, Avantis AV 928-2.5MW, Gamesa G114-2.5 MW and Gamesa 136-4.5MW) under various offshore wind conditions of the northern Emirates of UAE. The study analyzed the power curves of all the above wind turbine models to assess their capacity for wind power generation.

Analysis of Figure 13 shows that, at the offshore emirate of Ajman, turbine Aeronautica 47-750 MW with a cut-in speed of 3 m/s and rated output of 750 kW at 12 m/s, and the Gamesa 136-4.5MW turbine, with a cut-in speed of 3.5 m/s and rated output of 4000 kW at 12 m/s, are well-suited for the moderate wind speeds observed in the area. As shown in Figure 14, the offshore of the emirate of Ras Al Khaimah shows variable wind and power output profiles for the Gamesa 136-4.5MW and Avantis AV 928-2.5MW, suggesting that they are most appropriate for the location because these turbines have higher rated output and perform moderate to high wind speeds.

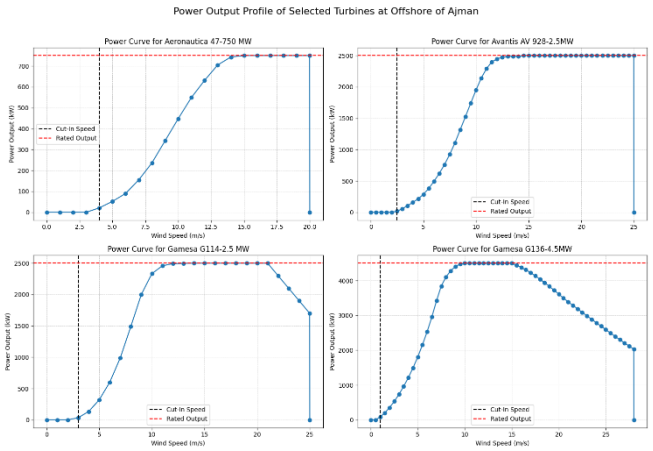

Figure 13.Power Output Profile of Selected Turbines at Offshore of Ajman

Analysis of **Figure 15** shows that the offshore emirate of Sharjah experiences higher wind speeds and higher variability in wind speed. Therefore, for this location, Avantis AV 928-2.5MW, with its optimal performance at higher wind speeds and rated output of 2500 kW at 15 m/s, and Gamesa

136-4.5MW, with its high-power output and rated output of 4000 kW at 12 m/s, are ideal for sustainable wind power generation.

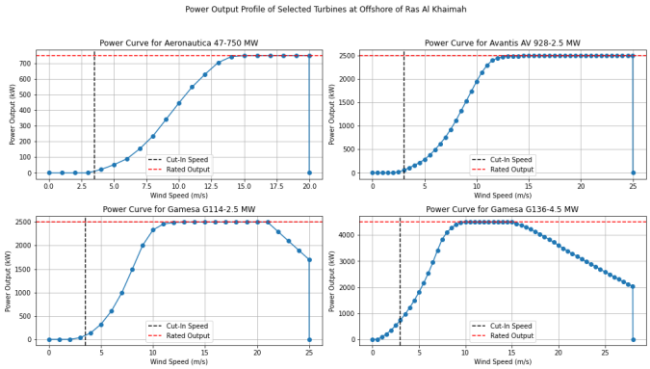

Figure 14. Power Output Profile of Selected Turbines at Offshore of Ras Al Khaimah

The offshore of Umm Al Quwain, as explained in Figure 16, shows moderate to high wind speed values, and the power out profile analysis indicates that, for this region, turbines with stable performance at these wind speeds are Gamesa G114-2.5 MW and Gamesa 136-4.5MW, and they can produce optimum wind energy at the location. In conclusion, the analysis of all the power-out profiles shows that the turbine Gamesa 136-4.5MW, which can operate and perform at moderate wind speed and has high power output, is the best choice for all four offshore locations in the northern Emirates. Specifically for the emirate of Sharjah and Ras Al Khaimah, where the analysis observed stronger and more variable wind conditions, the Avantis AV 928-2.5MW turbine is most suitable, and for Umm Al Quwain offshore location, the analysis shows that Aeronautica 47-750 MW and Gamesa G114-2.5 MW are most suitable for optimum power generation.

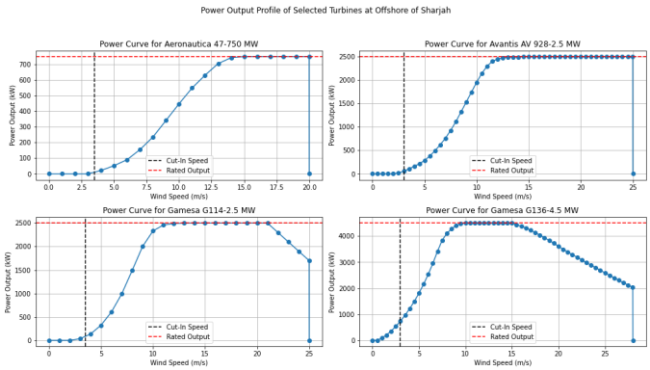

Figure 15. Power Output Profile of Selected Turbines at Offshore of Sharjah

No previous published studies are available on wind power output profiles of wind turbines and their feasibility analysis in the UAE region. However, [21] discussed various technological opportunities for installing renewable energy sources in the UAE, including Offshore wind turbines, and a recent study by [11] clearly explained why site-specific sustainable wind resource assessment is mandatory for sustainable wind energy development. This study fills the gap specific to the northern emirates of UAE, and based on the characteristics of geography and climate variability, this output will give direction for further in-depth studies and installation of wind monitoring systems at identified locations at turbine hub heights. Finally, this study greatly contributes to the existing literature by adding information about long-term wind analysis results, WPD analysis, and comparative analysis of various turbines' Power output profiles to select the suitable one. It will help with site-specific turbine selection and gives high implications for advanced turbine technologies capable of operating efficiently under changing wind conditions

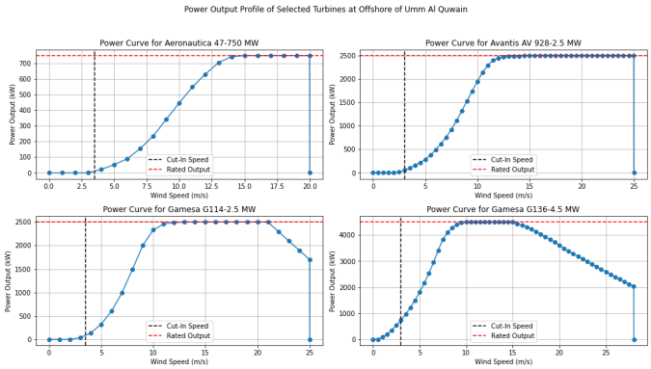

Figure 16.Power Output Profile of Selected Turbines at Offshore of Umm Al Quwain

VI. RECOMMENDATIONS:

Based on this study, the following recommendations are made for future wind energy studies in the Northern Emirates of the UAE. They can be extended to other parts of the UAE and GCC regions.

1. The study shows that the wind regimes change along offshore regions of the northern emirates, so it is crucial to select the specific wind turbine most suitable for the specific site for optimum wind energy generation. Generally, Gamesa 136-4.5MW is highly recommended for all offshore locations due to its high wind power output and optimum performance at moderate wind speeds. Avantis AV 928-2.5MW is most suitable for the offshore of Sharjah and Ras Al Khaimah, where the wind regime is more varying and stronger, and Aeronautica 47-750 MW and Gamesa G114-2.5 is suitable for the emirate of Ajman and Umm Al Quwain.

2. Based on the wind resource analysis of the offshore locations of the northern emirates, some locations, such as Sharjah and Ras Al Khaimah, show variable wind conditions; for these locations, it is highly recommended to install specific advanced turbines which can operate under varying wind conditions to optimise wind power production.

3. The effect of global climatic indices like El Niño and La Niña on the wind speed of the northern

emirates of UAE, should be further investigated in future studies

4. High wind power density in Sharjah and the emirates of Ajman and Umm Al Quwain offshore locations, which have steady, consistent wind speeds, should be integrated. With cooperation from each of the emirates, a combined wind farm can be installed to create a sustainable wind power system.

5. As a follow-up to this study, an economic cost-benefit and return on investment study is recommended to assess the financial sustainability of a wind power project that can be developed in these offshore regions.

6. The results of this study should be used for further strategic planning and decision-making, as well as inviting wind farm investors to develop wind power in offshore locations in the Northern Emirates of the UAE.

7. Implementing the result of this study and planning further wind energy research scope based on the result of this study result will contribute to achieving the UAE's COP28 goals.

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