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Assessment of Wind Power and Energy at the Coast of Balochistan, Pakistan

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ABSTRACT
The current study is confined to estimating the potential for wind energy in Balochistan's coastal areas, a region with immense potential for producing renewable energy sources. Here the initiatives are being discussed to generate more sustainable energy sources and whenever adjustments are made. Five-years (2018-2022) recorded wind data of Gwadar & Pasni from Pakistan Metrological Department Karachi, is used on different parameters. The data measured further processed and examined on a monthly and yearly basis. This study employs an integrated methodology, starting with the analysis of meteorological data for site-specific evaluation and wind energy generation.

Keywords: Wind energy, coastal site, wind direction, wind speed, wind Humidity, Balochistan

1. Introduction

To ensure sustainable development against global warming, one of the renewable energy resources is wind energy that is used to generate electricity. Being the oldest way to enhancing wind for grind grain and pump water with the use of so-called windmills (Manwell & McGowan, 2009), Currently, wind energy is the most prevalent source of power on Earth, with an estimated 300,000 to 870,000 GW of power available overall (Alhmoud & Wang, 2018).
Globally, wind energy is expanding. It is one of the renewable energy sources with the greatest growth rate and is the second-largest source of electricity generation, behind the hydropower. According to Global wind report 2023, an estimated 906 GW of wind power capacity is installed worldwide, representing a 9% annual growth rate and this new regional offshore and onshore installation projected to a new wind scenario outlooks, World's top market for wind installations are China, the United States, Brazil ,Germany and Sweden; While they accounted for 71% of all installations worldwide in 2022 (Global Wind Report 2023, 2023). It highlights the essential part that wind energy serves in shaping global energy policy for clean energy future.
Pakistan being an under developing South-Asian country has an extensive natural resource that might be utilized to produce wind energy in the form of secure and suitable wind velocity corridors. According to wind energy market trend repot in Pakistan, has adopted wind energy

Volume: 9, No: S 4, pp. 501-516
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significantly from the inception of the decade prior, mostly as a result of the government's increasing mandate for a renewable energy mix and improvements in wind energy technology that have reduced costs and increased efficiency (Market trends of Pakistan Wind Energy Industry, 2023). With an estimated 50,000MW of accessible wind power capacity, Pakistan has a large wind energy potential, making it a desirable location for wind energy development and investment (International Trade Administration, 2022). Wind characteristics and velocity spectra at ground level near the coastline can also be studied by Shiau et al., 1998.

Determining wind potential has become crucial for all wind power projects, many researchers have worldwide reported it. This led to the development of a number of wind power density determination models, including the Normal, Truncated Normal, Log Normal, Rayleigh model, Logistic, Log Logistic, Weibull, Inverse Weibull and Nakagami, Inverse Gaussian (Akgül, 2016; Kaoga, Raidandi , Djongyang , & Doka, 2014; Alavi, Mohammadi, & Mostafaeipour, 2016; Katinas, Marčiukaitis, Gecevičius, & Markevičius, 2017; Masseran, 2018). Among all the Weibull distribution is still a highly suitable and commonly utilized model with appropriate parameters in the wind trade sector (Kumar Pandey, 2020; Wais, 2017; Zhu, 2020; Werapun, Tirawanichaku, & WaewsaK, 2015). But before applying any statistical model, wind potential and characteristics analysis of any site is particularly important.

The current research is limited to the estimation of wind energy potential in coastal sites of Balochistan, a region having vast potential for the generation of renewables. Wherever changes are being made and plans to develop more sustainable energy sources could be considered, wind energy gains weight - especially in coastal regions where strong sea winds permanently blow. This research takes a comprehensive approach, from meteorological data analysis to computational modeling, and site-specific assessment for wind power integration. The present study is conducted in two coastal regions of Balochistan: Pasni & Gwadar, by taking 5-years (2018-2022) wind data on the parameters of wind speed, wind direction & wind humidity from Pakistan meteorological department, Karachi. This article's goal is to highlight wind resolution in Balochistan's coastal belt by examining daily, monthly, and yearly wind speeds, figuring out the wind's humidity component, and determining the wind direction at each location, which are crucial to initialization of any wind project on the particular location for enhancement of wind energy.

1.1. Site Description with Metrological Measurements

Balochistan is the largest province of Pakistan, covering an area of 347,190 square kilometers, or 43.6% of the country's total land area. Balochistan contains rocky plateau that is physically split into basins by peaks that are sufficiently high and rugged. The geographical region of Balochistan can be broadly classified into four separate zones: lowlands, deserts, lower highlands, and upper highlands. Balochistan province is located between 24° 53ˈ and 32° 05ˈ north latitudes and 60° 52ˈ and 72° 18ˈ east longitude (Introduction/Geographical Details; Balochistan, 2024). The present study is on the coastal areas of Balochistan. Wind characteristics are considered on the basis of 5-years metrological data on wind parameters like speed, direction & humidity are recorded diurnally. In the coastal region of Balochistan, two observatories have been chosen. Three hours apart, regular wind data is gathered at these locations, which are eight to twelve meters above the ground. Figure 1. shows the site map of the coast of Balochistan and Table 1 below represents the physical features of Gwadar & Pasni.

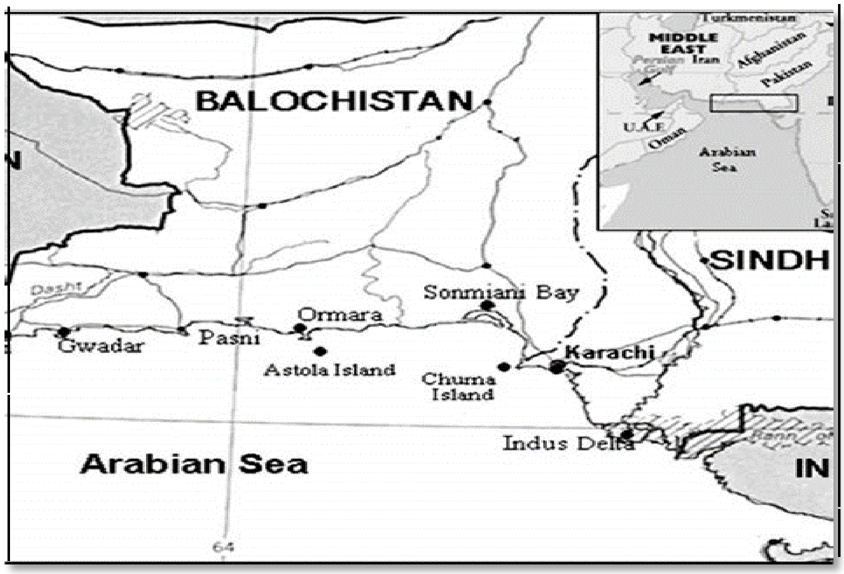

Figure 1. **Map of Coastal belt of Balochistan.**

Table 1. Physical features of the locations used in the study

Sites	**Pasni**	**Gwadar**
Latitude	25° 15' 60.00" N	25° 7' 35.0004" N
Longitude	63° 27' 59.99" E	62° 19' 20.9928" E
Max Temperature	75°F	92°F
Minimum temperature	58°F	83°F
Annual Humidity	75%	69%

An assessment of the wind energy potential at the Balochistan Coastal location reveals encouraging prospects for the advancement of renewable energy. The examination of wind patterns in the area reveals average wind speeds that are ideal and attributes that are appropriate for efficiently utilizing wind power. This implies that constructing wind turbines might be able to provide a sizable amount of electricity. However, many crucial elements are necessary for the economic viability and practicality of wind energy projects at Coastal sites. These consist of the upfront investment costs, continuous operating costs, grid connectivity choices, and the regulatory landscape. Determining the project's overall viability requires weighing these factors against the possible income from the sale of power. Furthermore, contrasting Coastal's estimated wind energy potential with that of other comparable locations or other energy sources offers vital information on the site's sustainability and competitiveness. Stakeholders can use these comparisons to make well-informed decisions on whether to pursue wind energy development at Coastal regions. Economic considerations also play a significant role in assessing the viability of wind energy projects (Junaid and Khan, 2017). This involves figuring out how much it costs to build and maintain wind turbines, in light of the evaluations and conclusions, the viability and financial advantages of wind energy development at the Coast of Balochistan is investigated

(Werapun, Tirawanichaku, & WaewsaK, 2015). Comparisons with other related sites or alternative energy sources may also be included to establish the scene and aid in decision-making.

2. Material and Methods.

The purpose of this study is to discuss wind characteristics of specific sites by taking monthly wind parameters data during five years (2018-2022), which are requested from CDPC, PMD Karachi. As wind has nature to show variation from time to time, which can be examined through recorded data. Wind speed on daily, monthly, and annual bases are analyzed. The five-year period (2018-2022) yearly wind roses are drawn that show us how the wind is distributed among the different directions and what proportion of the time we get wind from a given direction.

2.1.Wind Speed

Wind speed is one of the most important fundamental characteristics in producing electrified energy. Physically, speed of wind is dependent on pressure gradient, frictional forces & Coriolis effect (Hogan, 2010). Wind speed is determined by a few factors, such as climate and geography, and it varies with time and space. Since wind speed is a variable parameter, the exploitation of associated scientific approaches is usually overseen by estimated wind speed information. The most significant information on the wind spectra for its study is provided by the site's average wind velocity calculated by the term,

$$\bar{v} = \frac{\sum_i v_i}{n}, \tag{1}$$

where $\bar{v}$ stand for average wind velocity computed as the sum of wind speed data divided by total number of observations n.

2.2.Wind Direction

The wind direction corresponds to its origin. That indicates that it is moving toward the north and south poles as it rises or originates from the equator. It depends on the flow pattern of wind on the earth surface. The primary causes of wind flow patterns are temperature variations and Coriolis rotating force; as a result, early mariners gave these patterns different names, such as the trade wind, the easterlies, and the westerlies (Wind and Wind Energy , 2010). The following are generally recognized as the most prevalent winds on Earth, although these variations occur across continents and seas due to differences in locations and rates of heat transfer, as the earth's latitude range has been determined, we can see the different wind directions. By concerning the given phenomena wind direction of the specific sites can be analyzed, can further support the utilization of wind projects.

2.3. Wind Power Density

Wind is a driving force in wind energy systems since wind has power and can be predicted to have energy content. Therefore, it has been shown that wind energy can be transformed into either mechanical or electrical power when it is blowing.

Volume: 9, No: S 4, pp. 501-516
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Power density, expressed in watts per square meter (W/m²), provides a quantitative measure of the available wind energy at each site. Power density can be determined as

$$\frac{P}{A} = \frac{1}{2}\rho\frac{1}{n}\sum_{i=1}^{n} {v_i}^3 \qquad (2)$$

It can be observed that wind speed and power are proportionate, and that the air density, wind rotor area, and wind velocity's third power are the powers present in the wind stream. The primary component of the wind spectrum that determines the power available is velocity. Doubling the wind speed allows us to increase the available power eight times (Mathew, 2006).

2.4.Wind Humidity

Although wind humidity, or the quantity of moisture in the air when the wind was blowing, is not a significant factor in the majority of standard wind power evaluation techniques, it can affect turbine performance and actual energy yield. Reduced operational life spans are predicted to result from corrosion of turbine blades and other components in wind farms, such as those on the Coastal Belt (in Balochistan), caused by high relative humidity levels. Furthermore, the presence of water vapor in the atmosphere can somewhat change the density of the air as dense, humid air actually retains more energy and provides a somewhat similar benefit to wind power.

3. Results and discussion

By analyzing the local wind conditions, the wind energy potential can be estimated at Coastal location of Balochistan by selecting two metrological stations Gwadar & Pasni. Monthly wind speed average has been calculated from recorded five years wind speed data from 2018-2022, it is observed that maximum wind speed recorded are 6.96 m/s (April 2019) in Pasni & 8.16 m/s (April 2021) in Gwadar & while minimum wind speed is 1.44 m/s (November 2021) in Pasni & 2.95 m/s (December 2022) in Gwadar. Line trends of monthly wind speed variations are shown in Figures 2 and 3.

Table 2. Annual wind speed at Gwadar and Pasni

Years	Gwadar	Pasni
2018	4.74	4.06
2019	5	4.37
2020	5.43	3.64
2021	5.75	2.75
2022	5.6	3.03
Average	5.304	3.57

Annual average wind speed in Pasni & Gwadar are shown in Table 2, it is observed that 5-years annual average wind speed at Gwadar Balochistan is 5.3 m/s however in Pasni wind speed is 3.57 m/s.

Volume: 9, No: S 4, pp. 501-516
ISSN: 2059-6588(Print) | ISSN 2059-6596(Online)

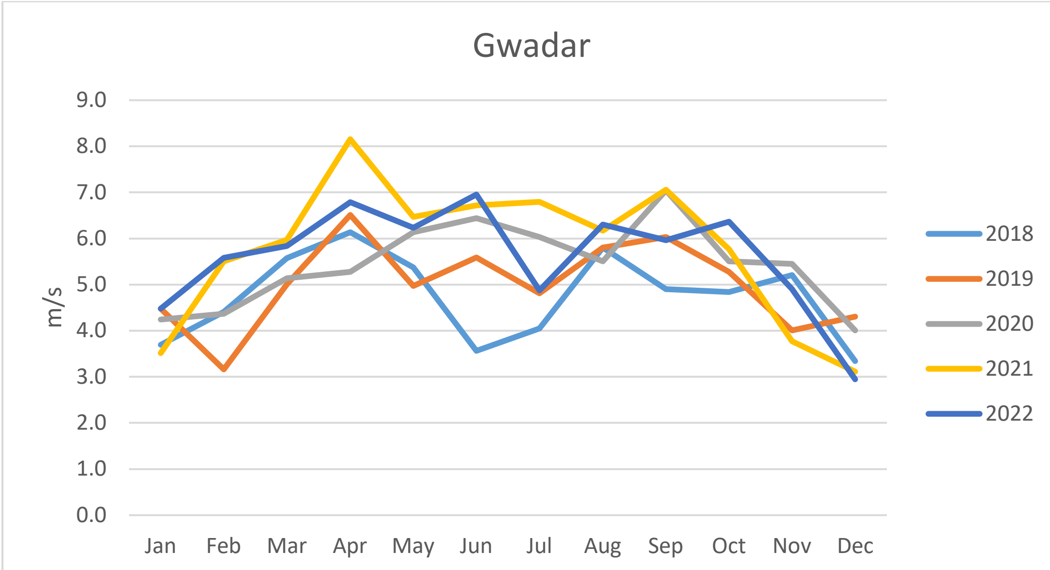


Figure 2**. Five years Monthly wind speed at Gwadar**

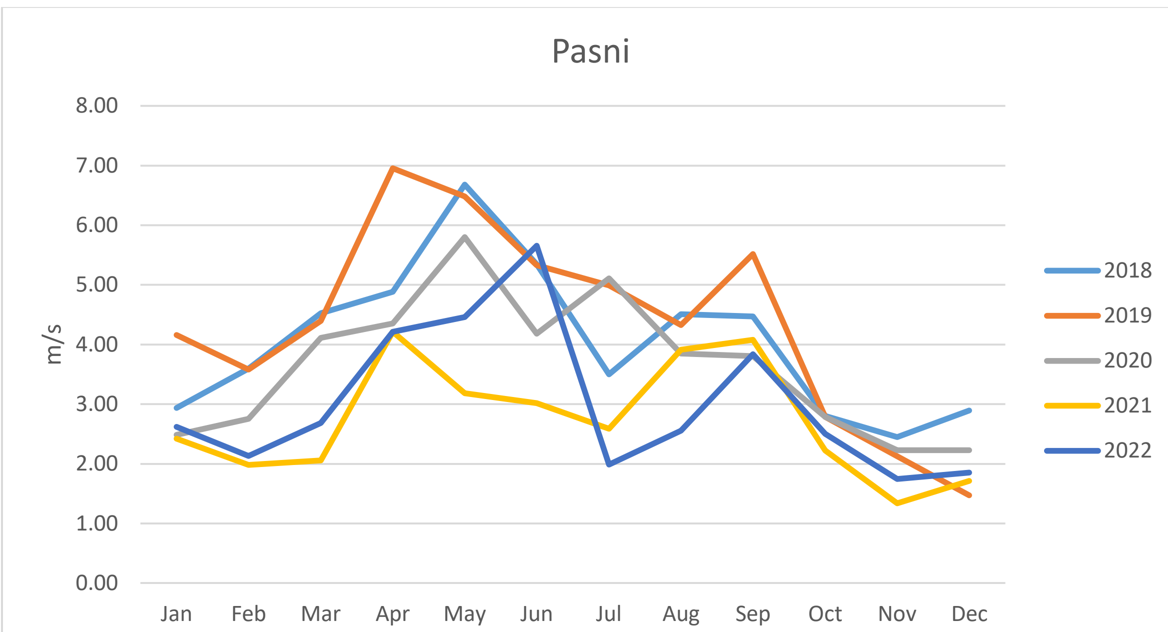


Figure 3. **Five Years Monthly wind speed at Pasni**

Volume: 9, No: S 4, pp. 501-516
ISSN: 2059-6588(Print) | ISSN 2059-6596(Online)

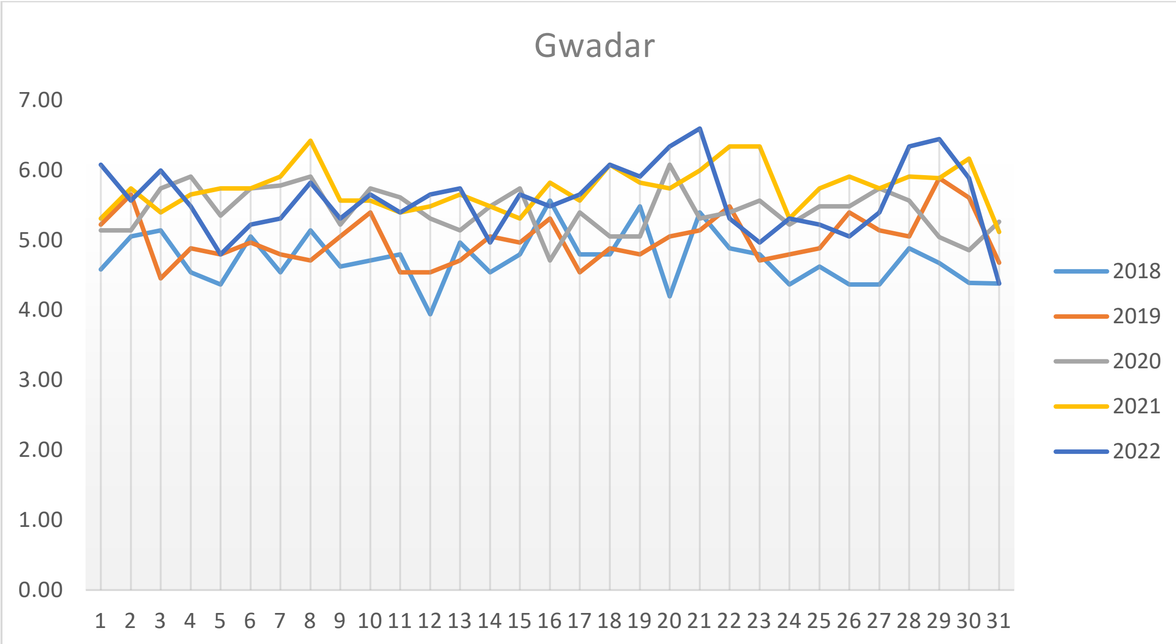


Figure 4. **Diurnal wind Speed at Gwadar during 5-years**

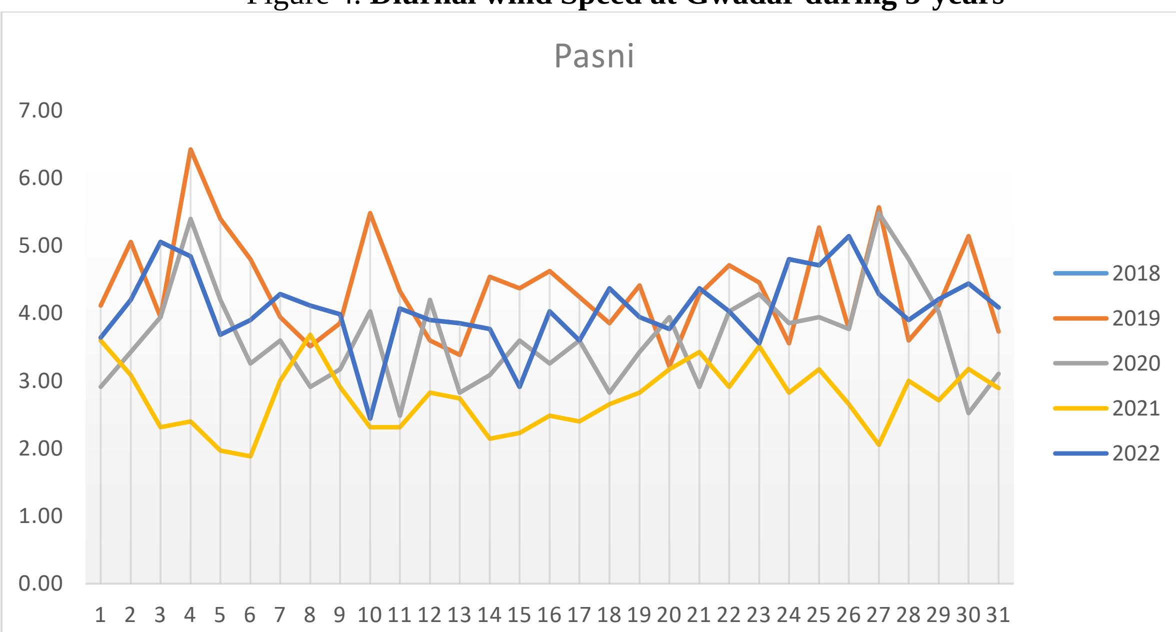


Figure 5. **Diurnal wind Speed at Pasni during 5-years**

Since wind involves temporal and spatial characteristics, it is estimated that wind variations occur in time and space. We think of time in terms of hours, days, months, years, and sometimes even decades. Diurnal wind speed at Pasni and Gwadar during five years is calculated which shows a good wind pattern under the range of 2m/s to 6.5 m/s in Pasni & 3.9m/s to 6.4m/s in Gwadar as shown in Figure 4 and 5. We understand that the short-spanned variation in wind

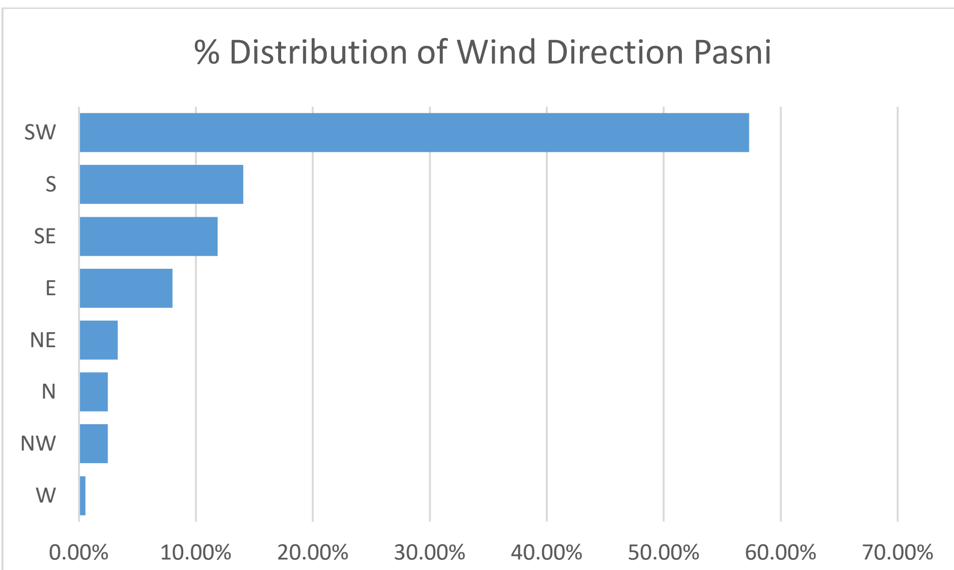
Volume: 9, No: S 4, pp. 501-516
ISSN: 2059-6588(Print) | ISSN 2059-6596(Online)

speed is caused by local geographic and meteorological factors, The wind may be stronger during the day than at night.

The wind radars indicate the direction of wind during the 5 years (2018-2022) over a specific time. Observations from five years recorded data are computed and illustrated with the help of wind roses. Table 3 below present monthly wind direction calculations during 2018-2022 in Pasni & Gwadar locations.

Table 3**. 5-Year Average Monthly Wind Direction of Coastal Sites**

Sites/Months	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Gwadar	139^0	121^0	122^0	127^0	127^0	110^0	105^0	122^0	126^0	128^0	110^0	127^0
Pasni	83^0	126^0	120^0	129^0	131^0	126^0	113^0	135^0	130^0	112^0	106^0	153^0



Volume: 9, No: S 4, pp. 501-516
ISSN: 2059-6588(Print) | ISSN 2059-6596(Online)

Figure 6. Percentage Distribution of Wind Direction at Pasni During 5-years (2018-2022)

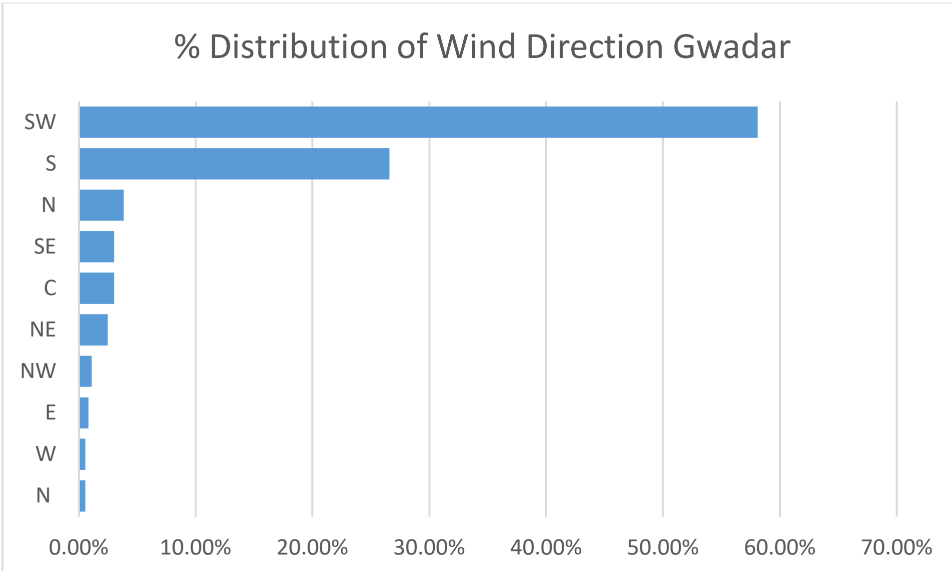


Figure 7. Percentage Distribution of Wind Direction at Gwadar During 5-years (2018-2022)

Distribution of wind directions are illustrated in Figure 6 & 7. Both regions indicating 60% values in southwest direction of wind during 5-years period 2018-2022. In Gwadar, the figure displayed 27% South direction. Figure 8 & 9 shows wind roses drawn from monthly wind direction observations which exhibit that wind prevailed in Southwest direction in month of August 2022 in Pasni while in Gwadar wind rose it shows August 2018 & December 2019 the most prevalent wind in southwest direction. The analysis of the wind direction distribution at various times points to the predominance of daytime winds over nighttime winds, further supported by the feature of mainland measuring locations.

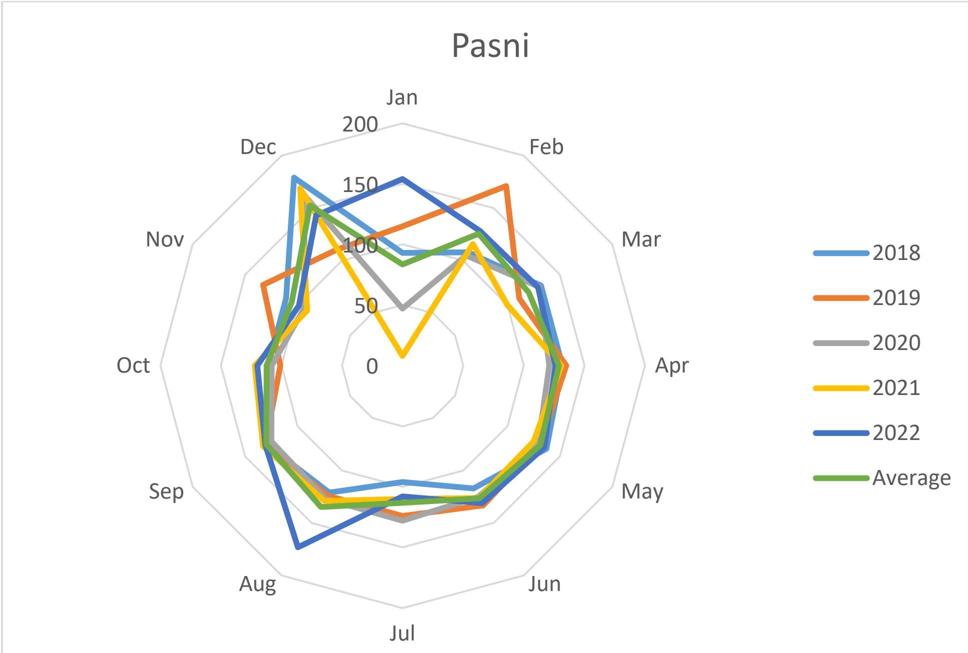


Figure 8. Monthly Wind Direction at Pasni During 5-years (2018-2022)

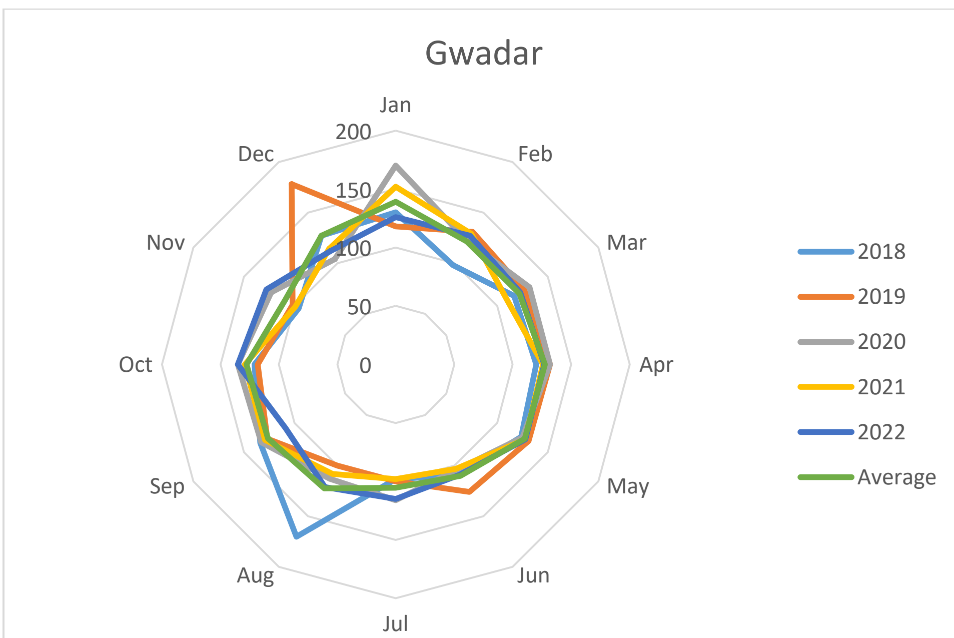
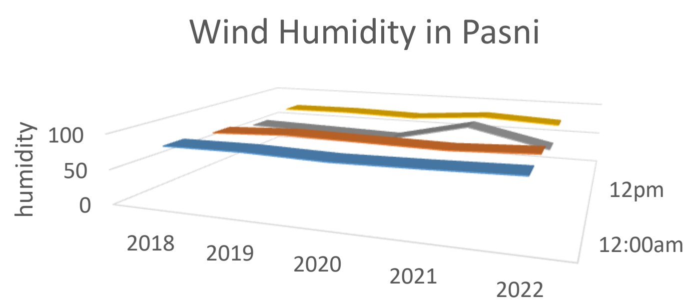


Figure 9. Monthly Wind Direction at Gwadar During 5-years (2018-2022)

The examination of Pasni and Gwadar's wind humidity levels highlights how these two sites wind energy potentials interact with one another in figures below. Humidity levels are recorded in both locations at three different timings; 1200am, 3:00am & 12:00 pm. With the use of

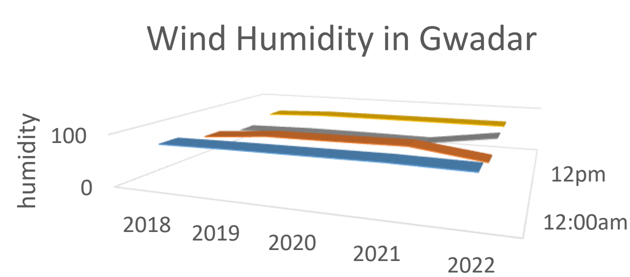
Volume: 9, No: S 4, pp. 501-516
ISSN: 2059-6588(Print) | ISSN 2059-6596(Online)

Microsoft Excel, it displays distinct patterns in humidity levels and their relationship to wind speed. The study provides a foundation for realizing how the variation in humidity levels in different coastal regions affects energy output and wind turbine efficiency. In actuality, these patterns can be utilized to gain a deeper understanding of the potential effects of humidity on wind energy production in Pasni and Gwadar.



	2018	2019	2020	2021	2022
12:00am	80	81	78	80	83
3am	75	80	78	76	81
12pm	65	62	59	86	60
Average	73	74	72	81	75

Figure 10. 5-years wind humidity in Pasni



	2018	2019	2020	2021	2022
12:00am	78	80	81	82	80
3am	63	74	75	77	59
12pm	50	53	53	52	73
Average	64	69	70	70	71

Figure 11. **5-years wind humidity in Gwadar**

To provide an extensive overview of the relative humidity in both Pasni and Gwadar throughout the year, Figure 10 & 11, provides detailed wind humidity data. This information is crucial for showing how humidity affects wind speed and the potential effects on wind energy generation.

The Pasni has continuously averaged a relative humidity that is marginally greater than Gwadar's, according to the chart above, which shows a five-year period of wind humidity data. Pasni's humidity is 62%. At 12:00 pm in day time, there are noticeable high points in both

Volume: 9, No: S 4, pp. 501-516
ISSN: 2059-6588(Print) | ISSN 2059-6596(Online)
regions. This pattern only demonstrates that, although both locations have high levels of humidity, Pasni experiences higher levels all year round. Regardless of the relative humidity variations, the same high wind speeds are maintained at both sites. The strong wind conditions in Pasni successfully offset the effects of the increased relative humidity, therefore it is not a significant factor that would negatively disrupt turbine efficiency. Because of this, Gwadar's low onshore humidity has produced a steady wind speed that has no effect on the turbines' efficiency or the amount of energy they generate.

After the wind parameters are understood, the next step is to evaluate how successfully wind turbines can convert the available wind energy into electricity. This means accounting for factors such as power production at different wind speeds, turbine efficiency, and how these factors interact with the specific wind conditions at Coastal. The annual wind power density during a time from 2018 to 2022 is shown in Table 4 below.

Table 4. Annual power density of specific sites

Years	2018	2019	2020	2021	2022
Gwadar	72.0	83.5	105.6	138.6	119.1
Pasni	51.9	70.0	38.1	16.8	25.5

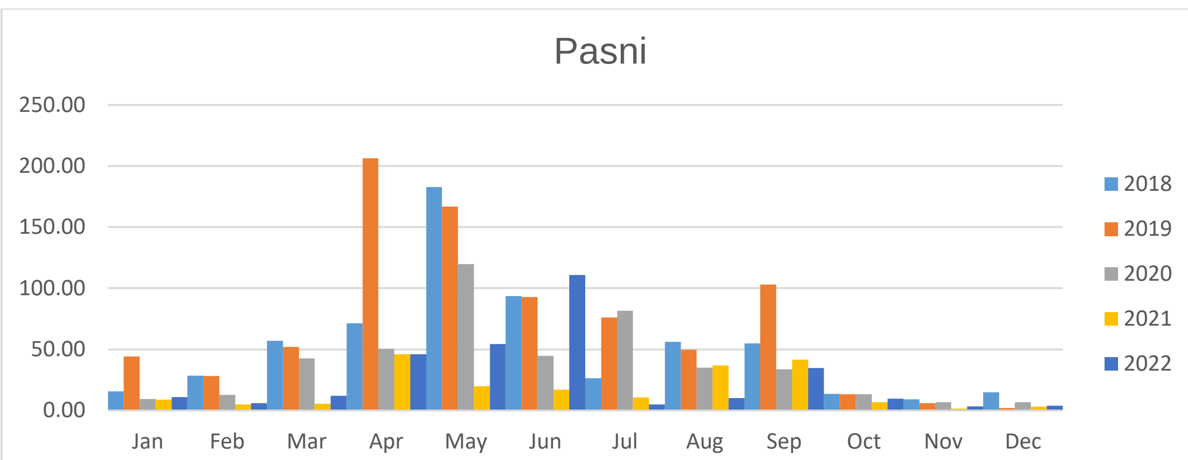


Figure 12. Monthly Power Density during (2018-2022) in Pasni

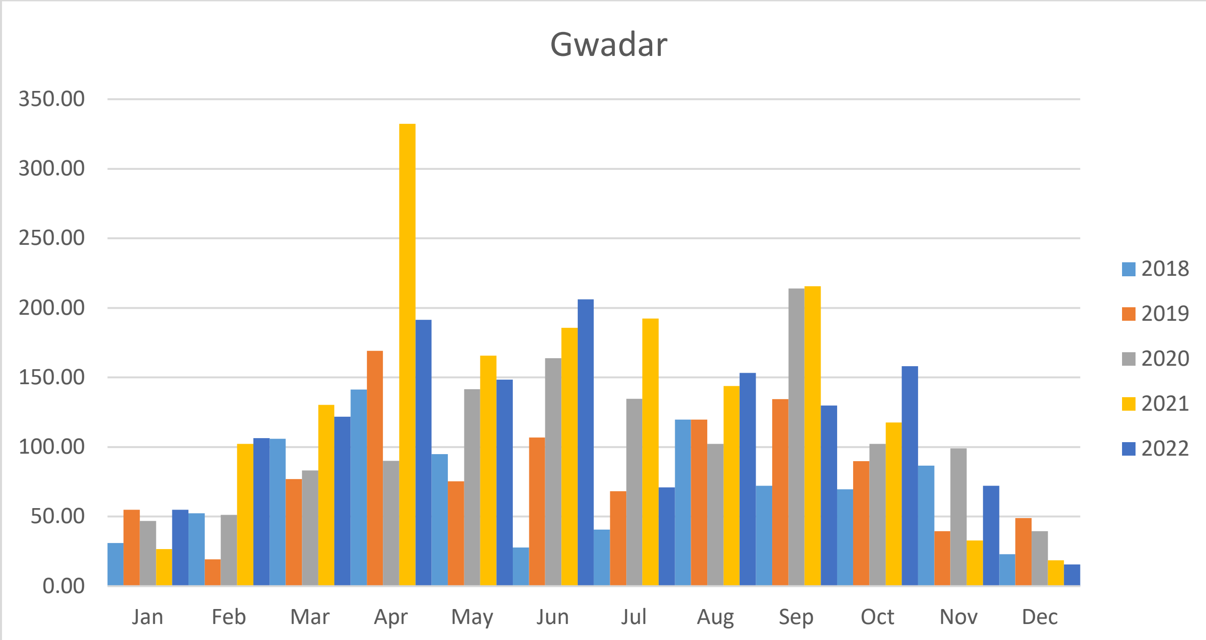


Figure 13. Monthly Power Density during (2018-2022) in Gwadar

The annual power density measurements obtained at Pasni and Gwadar are shown in Table 4, At two distinct coastal belt areas monthly mean power densities exhibit significant month-to-month variations as illustrated in Figure 10 & 11. In Gwadar, this power density varies between 19.28W/m^2 (Feb 2019) to 332.24 W/m^2 (April 2021) with five-year average estimated as 104 W/m^2 approx. In Pasni the power density ranges from 9.42W/m^2in Jan (2020) to the highest of 206.2W/m^2 in April (2019) and the five-year average value is about 40.4 W/m^2approx. It can be seen that the month of April in both sites shows a significant value of power density. Also, the months from April to September are more dependable for power generations.

Since these data provide factual information about the windy environment in these areas, they are essential to our research. We may evaluate effects on the infrastructure supporting telecommunications as well as consequences for environmental and regulatory concerns by analyzing these values. Analysis of these findings will enable us to make judgments about how safe and appropriate certain regions are for several types of technological use.

Conclusion

The current study area is also connected to the analysis of wind energy, and the coastal region of Balochistan is chosen as the study location based on meteorological data that has been recorded. A conventional meteorological measurement of wind speed data calculates how long the wind will take to pass a cup anemometer that is 10 meters high in 10 minutes. In conclusion, the following points are identified:

- Wind data from the two chosen locations in the Balochistan coastal region Gwadar & Pasni, over a five-year period (2018–2022) is observed and evaluated.

- Each of the chosen sites has a significant diurnal variation; for example, a higher mean wind speed is noted 6.5 m/s in daytime, with maximum typically occurring at 1200 PST. and it is as low as 1.5 m/s recorded in Pasni.
- The maximum wind speed and total wind power are received in the months of April & May in both regions. In Balochistan's coastal belt, June to September are the most favorable months for strong wind speed and wind power, and November to February are the least.
- The study reveals the average wind speed and power in selected sites during five years period (2018-2022) is;

Table 5. Average wind power in selected sites

Sites	Average wind speed m/s	Power Density
Gwadar	5.304	103.8
Pasni	3.57	40.4

- The proportion of time the wind was blowing from each direction can then be calculated by sorting the gathered wind data by wind direction.
- Indicating that the wind regime is consistent at all measurement sites during both the warm and cold seasons, as wind roses graphs are created for two distinct coastal belt locations and the wind direction considered most suitable in Southwest & South direction.
- Wind Humidity was examined during 5-years period in Pasni & Gwadar based on recorded data from the regional center, it is found that wind humidity in Pasni observed high than Gwadar.
- As from current research study, If the coastal location has wind energy potential, further extensive analyses and economic research are needed to determine the feasibility and maximize the potential of renewable energy projects.

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Competing interests
The authors declare that they have no competing interests.

Author's Contributions
The authors have contributed equally to the writing of this paper. They read and approved the manuscript.

Availability of data and materials.
All data analyzed during this study are included in this published article including useful references.

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