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Research article

# Strategic analysis of wind energy potential and optimal turbine selection in Al-Jouf, Saudi Arabia

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ABSTRACT

Wind power is considered one of the most environmentally friendly and rapidly growing form of renewable energy. This study aims at assessment of wind power potential for Al-Jouf region in Saudi Arabia. A long term historical wind speed data of 21 years (2000–2021) was analytically modeled using Weibull distribution function to determine the wind characteristics. The Weibull parameters and average wind speed for monthly and yearly were evaluated using MATLAB program. An online wind power calculator developed by Meteotest was used to evaluate the wind energy by selecting various turbines. Six types of commercial wind turbines of 3 MW capacity were selected for wind power assessment to optimize the turbine selection. Our analysis showed that average wind speed varies between 3.88 m/s and 4.99 m/s and an overall average wind speed is 4.38 m/s. The most frequent wind speed observed was 3.9 m/s with a probability of 20 % approximately. The Weibull distribution parameters, shape parameter "k" values ranged between 1.89 and 2.21 with an average of 1.98 and scale factor "c" values varied between 4.41 and 5.66 m/s with a mean value of 4.86 m/s. Performance evaluations of selected wind turbine models reveal that the Vestas V126 turbine outperforms others at the Al-Jouf site, generating an annual energy yield of 3779400 kWh at a capacity factor of 14.4 %. These results suggest that by constructing a wind farm consisting of 100 V126 turbines may compensate for the energy needs of 46000 individuals. These findings establish Al-Jouf as a viable location for utility-scale wind power projects, offering valuable insights for turbine manufacturers, developers, operators, and policymakers interested in deploying large-capacity turbines in the region. The method used in this study for wind power analysis and turbine selection is simple and helpful to provide an initial assessment about the site suitability and turbine selection without undergoing exhaustive efforts.

## 1. Introduction

The world's energy demand has increased significantly due to the rising human population and industrialization [1,2]. For decades, fossil fuels have been considered the primary energy source for meeting these demands, and a massive infrastructure was developed worldwide to extract and refine them [3,4]. However, the high demand has led to the rapid depletion of fossil fuel resources. Furthermore, using refined fossil fuels in transportation and power generation has caused an imbalance of carbon dioxide in the earth's ecosystem, leading to global warming [5–7]. This depletion of fossil fuel resources and imbalance in the ecosystem has prompted scientists to seek alternative and sustainable energy sources [8–10].

Scientists and researchers worldwide have explored various options for renewable and sustainable energy, and the research in this

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field is ongoing [11,12]. They are investigating options in solar, wind, biofuel, hydropower, nuclear, and geothermal fields to produce energy cheaply with minimal environmental harm [13,14]. Among these renewable energy sources, wind energy is one of the most promising and environmentally friendly sources [15,16]. The global wind power production capacity is around 650 GW, roughly one-third of that produced in Europe [17]. Advanced nations such as Germany and Spain aim to increase wind power generation by 5–7% in their overall power infrastructure [17].

Despite having one-fifth of the world's oil and gas resources, the Kingdom of Saudi Arabia (KSA) recognizes its responsibility to reduce oil and gas energy use and lower global pollution [18]. The KSA's 2030 vision supports transitioning the Kingdom's highly oil-dependent economy to alternative resources [19]. With an extensive coastline and flat, arid regions, the KSA has abundant wind resources. The Kingdom has plans to generate around 60 GW of energy from renewable resources, one-third of which will be produced from wind sources. To proceed with wind energy, the KSA has identified sites in different parts of the country to install wind power plants [12,18]. Part of this plan involves developing a mega-city called NEOM that will fulfill all of its energy requirements from renewable sources [20]. Wind farm sites have also been marked in various parts of the country, such as Hafar Al-Batin, Yambu, Riyadh, Al-Jouf, Tarif, and Jeddah, to generate and add wind power to the national grid [12,21].

Some socioeconomic factors and, wind and turbine capacity parameters need to be looked after before selecting a site for a wind power station [22,23]. The socioeconomic factors include public willingness to wind power, land acquisition from owners, environmental factors in the nearby areas, governmental legislation, and power production cost [16,24]. Wind parameters that need to be carefully considered include wind speed, frequency of wind speed distribution, air density, and wind flow direction. The turbine parameters include rotor diameter, hub height and power capacity [25]. Other factors like ground conditions, access to the electricity grid and appropriate ground and topography are also critical [21,25].

This study focuses on highlighting the potential of wind energy; hence, wind parameters will be considered in detail. The wind speed and frequency of the wind speed are two essential parameters for choosing a site for the wind farm. Wind speeds between 3.5 and 4 m/s are regarded suitable for small wind turbines, whereas wind speeds between 5.8 and 8 m/s are considered suitable for commercial wind turbines [26–28]. The second parameter related to efficient wind power production is how often the wind blows, which can keep the turbine rotor moving. If a range of wind speeds of 3–5 m/s keeps turbine spinning for 70 to 80 percent of the time it is considered to be economical [26,29,30]. The high-density air exerts more force on the turbine blades for easy rotation. This attribute of the wind makes it popular to install most of the initial wind power installation near coastal areas [23,29]. The dense coastal air also has some drawbacks due to corrosion-related problems, which require high turbine maintenance costs and effective working life reduction of up to 10 years [6,28]. The air density also changes with the height; a study suggests that a change in wind turbine height from 10 m to 50 m increases efficiency by up to 37 %. Although with altitude, there is a decrease in density but an increase in wind speed due to minimum interference [23,28]. The direction of wind flow and wind interruption with the nearby structure also hamper efficient wind power production [25,28].

The wind atlas data reported by different researchers show that wind speed in most areas of the Kingdom is between 6 m/s to 8 m/s, which is suitable for generating wind power [19,28]. Within this range, medium and large wind power generators can be installed. Despite wind energy's increasing penetration, its variability makes grid integration difficult. Wind energy output fluctuates due to spatial and temporal variations in wind speed. Therefore, forecasts of future wind speeds are necessary for incorporating wind power into the electric system. Serious efforts have been made to analyze the wind speed and power density by using different modeling tools; among them, lognormal distribution, Rayleigh distribution, Neural network, and Weibull distribution are extensively reported [20].

Rehman et al. [25] used Weibull distribution to model the wind speed distribution for 10 locations in Saudi Arabia. Shape parameter ($k$) and scale parameter($c$) were determined for selected sites. k values varies between 1.95 and 2.6 and c values between 3.07 and 4.98. The central region, Riyadh and Qassim observed low values of k and c. A seasonal trend was observed in the values of parameters, increasing from January to July and decreasing onward. Rehman et al. [29] also investigated the wind power potential for coastal locations of Saudi Arabia. Wind turbines for various capacities between 150 and 2500 kW were compared for the power production and capacity factor. Yanbu was determined the best location to harness wind energy among other sites. Rehman and co-authors [31] performed analysis of long term wind speed data and estimated energy production by using turbines of different capacities for Rafha. HOMER and RetScreen methods were used for energy yield assessment. The analysis suggested the unsuitability of the site for large power plant. Mukhtar et al. [28] determined the wind speed characteristics and wind energy potential for different sites of Saudi Arabia by using the Weibull probability density function. The Maximum Likelihood method was the most accurate method for estimating Weibull parameters and wind speed. Yanbu and Haql stations were found to be more suitable for large-scale wind power installation based on higher wind speed and power density. Murad et al. [32] evaluated the wind energy potential of Socotra in Yemen through Weibull distribution. The Analysis was done at different heights, 10 m, 20 m and 30 m and turbine selection was optimized based on the capacity factor. Alanazi et al. [33] used six different statistical methods to determine the most suitable method for Weibull parameters for wind energy assessment in Qassim region. The Moment Method was found to be the most appropriate method for estimating wind power density and concluded that Qassim is suitable for small off grid projects. El Alaoui et al. [34] applied machine learning models and statistical methods to predict the heating energy usage of a building. The machine learning model proved to be more efficient than the statistical model "SARIMA". Husin et al. [35] assessed the cost effectiveness of green buildings by employing a Block Chain-BIM methodology. They found that including renewable energy sources enhances the economic performance of green buildings. Qing et al. [36] determined wind speed characteristics and wind power analysis by utilizing the wind power data for a wind farm in Cape Verde. Wind distribution was determined through the Weibull distribution model as well as power estimation. Also, an equivalent power curve was developed based on uncertainty analysis of the wind resource to predict the reserve storage requirement and capacity of the storage system considering power ramps. Serban et al. [37] evaluated wind energy potential for two sites in Romania by analyzing the wind speed characteristics through Weibull and Rayleigh distribution models for a wind speed data of one year. Weibull distribution model was found more accurate and the wind speed that produces the maximum energy has more influence on wind power potential than average and most frequent wind speed.

AlQdah et al. [38] assessed wind energy potential of Medina by analyzing the historical wind speed data through Weibull distribution model. A low-capacity wind turbine Aventa Av-7 was tested for energy production and recommended for the site due to low wind speed with an average value of 2.9 m/s. Kumar et al. [21] used multiverse optimization to determine the Weibull parameters to assess the frequency and distribution of wind speed for a region in India. Rafique et al. [39] performed the feasibility analysis of a 100 MW wind farm for different locations in KSA using RETScreen and found it viable in terms of all performing indices for all selected locations, Dhahran being the most favorable. Marouani et al. [40] did a techno-economic analysis and optimized cost of energy(COE) for Dumat Al-Jandal wind farm project. The minimum cost of energy was obtained at a hub height of 105 m and rotor diameter 150 m. COE calculated was 39–48 % higher than that of quoted by the project consortium. Kamel et al. [41] studies feasibility of a 400 MW wind farm at Dumat Al- Jandal by simulating through SAM software and found it economically feasible. Ouerghi et al. [42] studied wind energy potential and feasibility for Saudi Arabia by using historical data for different locations. Weibull distribution function was used for wind speed characteristics. Imam et al. [43] employed machine learning methods to forecast the wind and solar resource variability for Saudi Arabia. The study concluded with promising potential for these resources and viability both technically and economically. Shaahid et al. [44] also did a feasibility study of 15 MW for two geographically distinct non-coastal locations in Saudi Arabia. The northern site performed relatively better than the southern counterpart. Alfawzan et al. [20] analyzed the wind energy potential and feasibility for future NEOM cities in KSA. The wind speed data was modeled by Weibull distribution. The study findings demonstrate that this site is viable for building a commercial wind power plant. 3.2 MW capacity turbine yielded the highest capacity factor about 41 %.

The above literature survey indicates that the possibility of harnessing wind power in a certain location should be thoroughly examined as a part of feasibility study on wind energy. This assessment comprises several crucial components, including a comprehensive examination of the wind resource that utilizes historical wind data to understand patterns and fluctuations, an assessment of site suitability that considers factors such as terrain, elevation, and environmental conditions, and the selection of the most appropriate wind turbine technology based on on-site characteristics [45]. An incorrect selection of sites and turbines can result in costly or highly interrupted power generation or complete failure. The survey also emphasizes the potential of wind energy and the Kingdom of Saudi Arabia's desire to shift to renewable energy. In this regard a large wind farm of 400 MW capacity is to be installed in Al-Jouf region under the National Renewable Energy Program of the Kingdom's Vision 2030 [46].

Hence, by considering all these factors mentioned above, the scope and contribution of this work is summarized in the following paragraph:

The main focus of this paper is to assess the wind energy potential of Al-Jouf location because detailed studies are rarely reported for this location, and it is one of the potential sites for future wind power station in the Kingdom of Saudi Arabia. Hence a comprehensive analysis of wind data and its modeling is warranted to determine the wind characteristics imperative for an efficient wind farm operation. The wind speed data is modeled by employing Weibull distribution function which fits well with the actual data. The data analysis indicates that overall average wind speed is 4.38 m/s and the Weibull distribution parameters, shape parameter "k" and scale factor "c" with an average value of 1.98 and 4.86 m/s respectively. Most importantly a simple and freely available power calculator is used to evaluate the power potential of the region based on Weibull parameters and various commercial turbines to optimize the turbine selection. To the best of the author's knowledge this approach is hardly reported in other studies and for this region specifically. Vestas V126 of 3 MW capacity was found the best performing machine producing power at a rate of 3780288 kWh per year. This choice is also in agreement with the selected turbine offered by bidders and consortium of the proposed project in this region. Finally, the assessment of wind power at Al-Jouf will provide an insight to assist the policy makers, energy organizations, investors, turbine manufacturers and project designers to make informed decisions by using this simple methodology without undergoing exhaustive

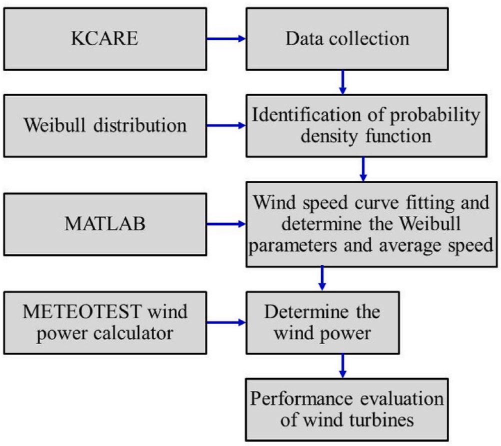


**Fig. 1.** Framework design adopted for the study.

efforts.

## 2. Materials and methods

### 2.1. Methodology

The study employs a comprehensive methodology that includes data collection, modeling of wind properties, analysis of wind speed frequency distribution, and assessment of wind energy. Fig. 1 shows the methodology framework design that was chosen for this study.

### 2.2. Wind speed data

Wind speed data was collected from King Abdullah City for Atomic and Renewable Energy (KCARE) for the location of Al-Jouf. The metrological data over a period of 21 years from January 2000 to December 2021 have been obtained from the solar and wind resource monitoring stations of KCARE program. The wind speed was measured at 10 m above the ground level using an anemometer with an accuracy of 0.1 m/s. The data included wind speed measurements taken every hour.

### 2.3. Wind speed data analysis and modeling

Since the wind is intermittent and its speed changes frequently. Therefore, statistical probability distribution functions must be utilized to predict the wind behavior over a long period of time. Weibull distribution model was chosen to model the wind speed distribution data due to its simplicity, accuracy and flexibility to deal with a wide range of data. Many other researchers have used Weibull distribution to estimate the potential of wind energy and found it fits well with the wind speed data [21,25,27,38]. MATLAB software was utilized to perform the necessary statistical computations. The mathematical expression of the Weibull distribution's probability density function(PDF) to assess the wind speed is represented by Equation (1) [25,28,38].

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^{k}}, \tag{1}$$

where $v>0; k, c>0$.

$f(v)$ represents the probability of observed wind speed $v$, $v$ is the wind speed(m/s), $\boldsymbol{k}$ is the Weibull shape parameter and $\boldsymbol{c}$ is scale parameter.

Furthermore, the Weibull shape parameter $k$ is dimensionless, while the parameter $c$ has unit of m/s similar to speed. The Weibull shape parameter k, also referred to as the Weibull slope, quantifies the degree of skewness in the distribution. It determines the consistency of wind speed at a given location. The scale factor c determines the wind potential, how windy the region is. A larger value of c indicates higher wind speed and more wind energy potential of the location [36].

The cumulative distribution function(CDF) $F(v)$ associated with Weibull PDF of Equation (1) is given as follows [25]:

$$F(v) = \int_0^v f(v)dv = 1 - e^{-\left(\frac{v}{c}\right)}. \tag{2}$$

where $F(v)$ represents the probability of observing a wind speed that is either equal to or lower than $v$.

It is clear from equations (1) and (2) that wind distribution curve is greatly affected by the values of Weibull parameters k and c. Hence accurate estimation of these values is essential. The maximum likelihood approach is used here as one of the most suggested approaches for estimating Weibull distribution parameters for wind power analysis [47]. The $c$ and $k$ parameters are estimated by using mathematical expressions given by equations (3) and (4) respectively [38].

$$k = \left(\frac{\sum_{i=1}^{n} v_i^k \ln v_i}{\sum_{i=1}^{n} v_i^k} - \frac{\sum_{i=1}^{n} \ln(v_i)}{n}\right)^{-1} \tag{3}$$

$$c = \left(\frac{\sum_{i=1}^{n} (v_i)^k}{\sum_{i=1}^{n} v_i^k}\right)^{\frac{1}{k}} \tag{4}$$

Where, the $v_i$ represents the *ith* wind speed which is taken every 1 h, and the $n$ is the total number of hours from January 2000 to December 2021. The average wind speed ($v_m$) and standard deviation ($\sigma$) were calculated using equations (5) and (6) respectively:

$$v_m = \frac{1}{n}\sum_{i=1}^{n} v_i \tag{5}$$

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(v_i - v_m)^2} \tag{6}$$

### 2.4. Estimation of wind power potential

Wind power potential was estimated by using a wind power calculator software developed by METEOTEST company and available on Swiss wind energy website. This calculator evaluates the wind power based on Weibull distribution and power curve of the wind turbine [48]. Various models of widely used wind turbines of 3 MW capacity were selected from the database to evaluate wind power generation. The Weibull parameters k and c estimated through Weibull probability density function were utilized as input parameter in the power calculator to find the power generation and other characteristics of turbine performance. It was assumed that turbine is available 100 % without breakdown, maintenance schedule and no icing factors.

## 3. Results and discussion

### 3.1. Wind source analysis

Wind power potential at a site depends on the area's characteristics, wind speed and characteristics of the wind turbine. Wind power is proportional to the cube of the wind speed as given by Equation (7) [28]:

$$P_{wind} = \frac{1}{2}\rho A v^3 \tag{7}$$

Where $\boldsymbol{\rho}$ represents air density, $\boldsymbol{v}$ is wind speed and $\boldsymbol{A}$ is swept area by turbine rotor depends on the diameter of the rotor blade.

Analyzing and modeling wind speed is crucial to estimate wind power generation at a given location. Wind speed data is modeled by assuming it follows the Weibull probability distribution function. The dataset comprises a total of 210,846 observations. To avoid misinterpretation, the conditions $v_i > 0$ and $v_i <= 30$ were applied, resulting in a total of 189,904 observations being considered for further Analysis. Since $v_i = 0$ represents no wind condition $v_i >= 30$ will be a thunderstorm condition which is rare to occur. So, these values were excluded. Table 1 presents the average wind speeds for each month. As shown in the table, the maximum wind speed of 4.54 m/s was recorded in April, while the minimum wind speed of 3.06 m/s occurred in December. In the summer months (March to August), we had higher wind speeds, coinciding with the high-energy demand period in the Kingdom. Therefore, high wind speeds during peak load time can increase wind energy production.

Table 2 provides the yearly average wind speed and standard deviation, as well as the estimated values of parameters $c$ and $k$ for each year. The table also includes the overall average wind speed, standard deviation, and values of parameters $c$ and $k$ for a comprehensive analysis.

The results presented in Table 2 indicate that the wind speed dataset is relatively uniform, as evidenced by the low standard deviation values. The average wind speed varied between 3.88 m/s (minimum) and 4.99 m/s (maximum) from 2000 to 2021, considered adequate for wind energy production. The shape parameter "$k$" ranged between 1.89 and 2.21. A higher value of $k$ indicates a constant wind speed, with most of the data clustering around the mean value. Conversely, a lower value of k indicates a more significant variability in wind speed [36,47].The minimum and maximum $k$ values were observed in 2002 (1.89) and 2005 (2.21), respectively (refer to Table 2). The average value of $k$ was found to be 1.976, which is reasonable and indicates a relatively small spread in wind speed. The scale parameter, "$c$," represents the wind speed characteristics of the distribution. The calculated $c$ values varied between 4.41 and 5.66 m/s, with a mean of 4.857 m/s for the study period.

The frequency of wind speeds was determined using the Weibull probability density function, and the results for all years are shown in Fig. 2. The figure shows that the wind speed frequency gradually increased from 2000 to 2021. The most common wind speed was around 4.5 m/s, which occurred yearly with some percentage variation. This trend continued until wind speeds of 12–15 m/s, after which the frequency fell to zero, indicating a meager chance of wind speeds exceeding this range. Even if such high wind speeds were to occur, they would have minimal impact on the overall performance of the wind energy system.

The Weibull distribution plots overlaid on the wind speed histograms are depicted in Fig. 3. The Weibull curves fit well with the wind histogram data, which validates the use of the Weibull distribution for wind speed data analysis. The most frequent wind speed of around 3.9 m/s with a probability of approximately 20 % is observed, with minor variations.

**Table 1**
Average monthly wind speed from 2000 to 2021 in Al-Jouf.

| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wind speed m/s | 3.58 | 3.96 | 4.38 | 4.54 | 4.47 | 4.28 | 4.37 | 3.98 | 3.44 | 3.41 | 3.16 | 3.06 |

**Table 2**
Weibull distribution parameters and average wind speed from 2000 to 2021.

| Years | Measures | | Parameters | |
|---|---|---|---|---|
| | Average wind speed(m/s) | Standard deviation | *c* (m/s) | *k* |
| 2000 | 4.715 | 2.481 | 5.35 | 2.04 |
| 2001 | 4.993 | 2.544 | 5.66 | 2.10 |
| 2002 | 4.873 | 2.787 | 5.53 | 1.89 |
| 2003 | 4.715 | 2.528 | 5.35 | 2.00 |
| 2004 | 4.290 | 2.258 | 4.87 | 2.03 |
| 2005 | 4.482 | 2.175 | 5.09 | 2.21 |
| 2006 | 4.204 | 2.186 | 4.77 | 2.06 |
| 2007 | 4.282 | 2.355 | 4.86 | 1.95 |
| 2008 | 3.975 | 2.172 | 4.51 | 1.97 |
| 2009 | 4.088 | 2.301 | 4.64 | 1.91 |
| 2010 | 4.094 | 2.280 | 4.64 | 1.93 |
| 2011 | 3.886 | 2.052 | 4.41 | 2.03 |
| 2012 | 4.032 | 2.241 | 4.57 | 1.94 |
| 2013 | 4.376 | 2.306 | 4.96 | 2.03 |
| 2014 | 4.187 | 2.280 | 4.75 | 1.97 |
| 2015 | 4.267 | 2.334 | 4.84 | 1.96 |
| 2016 | 4.173 | 2.293 | 4.73 | 1.95 |
| 2017 | 4.145 | 2.352 | 4.70 | 1.90 |
| 2018 | 4.261 | 2.398 | 4.83 | 1.91 |
| 2019 | 4.096 | 2.189 | 4.65 | 2.01 |
| 2020 | 4.176 | 2.334 | 4.74 | 1.92 |
| 2021 | 3.919 | 2.081 | 4.44 | 2.01 |
| Overall | 4.283 | 2.327 | 4.857 | 1.976 |

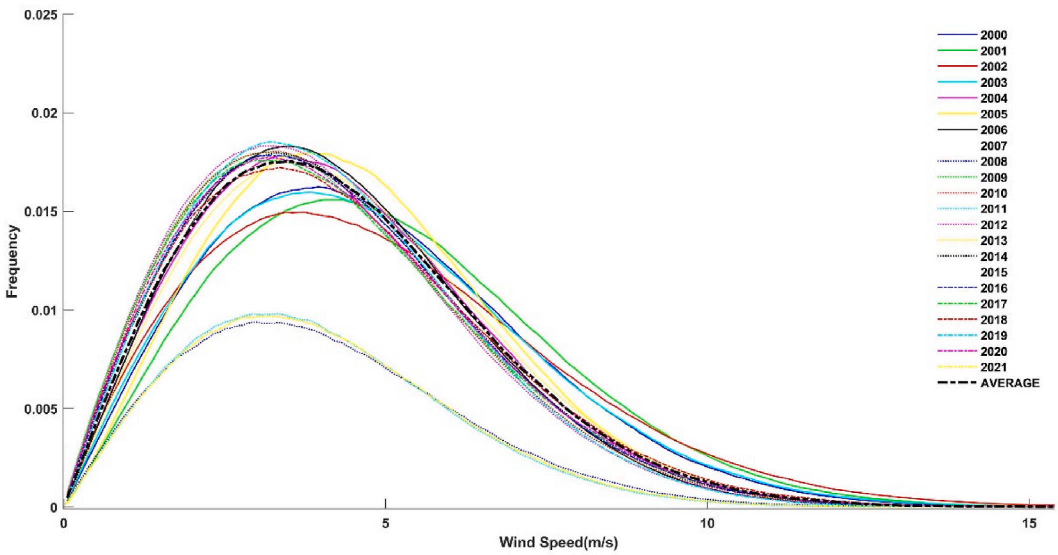


**Fig. 2.** The Weibull distribution 2000–2021.

### 3.2. *Wind power production and turbine selection*

The energy production of the wind turbine was estimated using a power calculator from The Swiss Wind Power Data Website. The tool utilized the power curve of the wind turbine and the Weibull probability distribution of wind speed density [48]. The long-term historical data shown in Table 2 was used to calculate the mean annual wind speed and Weibull distribution parameters, which suggested that the selected site had good strength and frequency of available wind speed. To estimate the annual energy yield, a large-capacity turbine was selected. For this study, turbines with a rated capacity of 3000 kW from various manufacturers were chosen for comparison. The air density was calculated using the annual average temperature and pressure measured on the surface, resulting in a value of 1.14 kg/m$^3$.

Fig. 4 displays a representative power curve plot for one of the selected wind turbines Vestas V126. Since the power curves of all the turbines show similar trends and features, therefore for the sake of brevity and clarity of the pictures only one sample plot is shown here. These power plots were generated from the wind power calculator using the calculated Weibull distribution parameters. Each

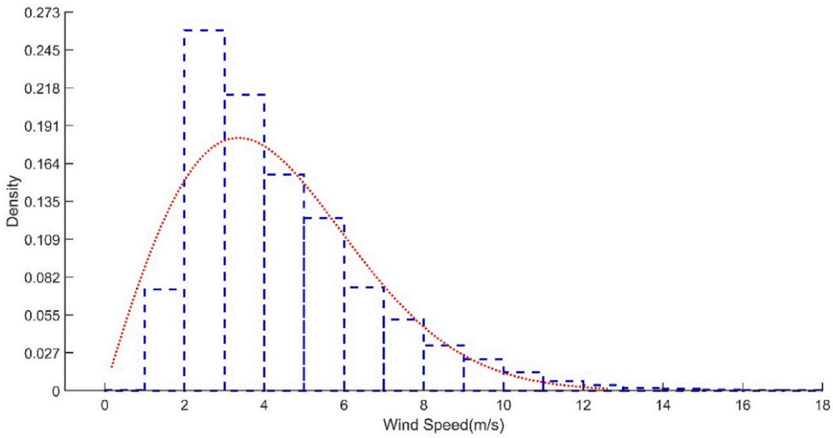


**Fig. 3.** Weibull wind density distribution histogram.

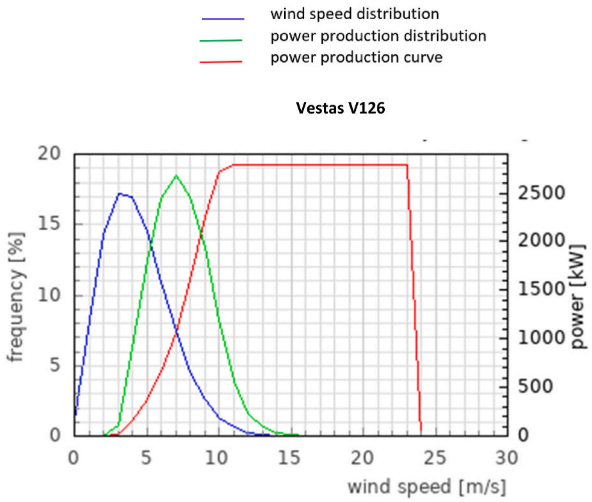


**Fig. 4.** Power curve of Vestas V126 turbine for Al-Jouf [48].

power curve is divided into four separate regions of power and wind speed. The first region is the cut-in speed, which represents the minimum speed required for the turbine to start producing power. Below the cut-in speed, the turbine efficiency is zero. The second region is the maximum power coefficient zone, which defines the turbine pitch control. In this region, the turbine is operated at maximum efficiency with a constant tip speed ratio to produce the maximum output power. The rated speed is when the turbine starts producing the maximum power at the rated capacity. Fig. 4 also shows a constant power region of power curve, in which the turbine power remains constant even for wind speeds more significant than the rated speed. In this region, the rotor is restricted to operating at speed within the safe limits set by the turbine and system component designs, even if higher wind speeds are available. Lastly, there is a cut-out speed region, representing the speed at which the rotor is switched off if the wind speed exceeds the cut-out speed. The turbine

**Table 3**
Power generation of various wind turbines for Al-Jouf [48].

| Turbine producer/model | Vestas V126 | Enercon E115 | Nordex N117 | Senvion M122 | Vensys 120 | Leitwind LTW 101 |
|---|---|---|---|---|---|---|
| Capacity (kW) | 3000 | 3000 | 3000 | 3000 | 3000 | 3000 |
| Rotor diameter (m) | 126 | 115.7 | 116.8 | 122 | 120 | 100.9 |
| Cut in speed (m/s) | 3 | 2 | 3 | 3 | 3 | 3 |
| Cut out speed (m/s) | 24 | 26 | 26 | 23 | 23 | 26 |
| Power production (kWh/year) | 3779400 | 3404977 | 3312349 | 3614027 | 3396805 | 2425578 |
| Capacity factor (%) | 14.4 | 12.9 | 12.6 | 13.8 | 12.9 | 9.2 |
| Full load hours (h/year) | 1259 | 1134 | 1103 | 1213 | 1131 | 808 |
| Operating hours (h/year) | 6693 | 7941 | 6693 | 6693 | 6693 | 6693 |

stops working to protect the blades and other components. From the power curve in Fig. 4 and the rest of power plots not shown here, it is observed that that the cut-in speed for all turbines is approximately 3 m/s, and the cut-out speed is beyond 22 m/s. Therefore, all turbines can produce power for the selected site as the average wind speed value 4.28 m/s is above the cut-in speed.

Fig. 3 indicates that wind speeds of 20 m/s and above are rare in Al-Jouf, with the frequency dropping to zero beyond 15 m/s. Thus, the selected turbines are expected to operate mostly without triggering the cut-out speed and causing any turbine damage. Table 3 presents the specifications and power production of the selected wind turbines using the power calculator, with a turbine availability assumed to be 100 % and no losses due to downtime, icing, transformer losses, park effects, etc. Notably, all turbines have a cut-in speed of 3 m/s, which is lower than the average wind speed of 4.28 m/s at the site determined through Weibull distribution by analyzing the data. This implies that all selected turbines can generate power. The cut-out speed ranges from 23 m/s to 26 m/s for the selected turbines, which is also a rarity in Al-Jouf, as demonstrated by the Weibull distribution of the speed in Fig. 2. Consequently, it can be concluded that the turbine will run for most of the time. Table 3 and Fig. 5 show that the Vestas V126 produces the highest power output of 3779400 kWh/year and the highest capacity factor of 14.4 %. The capacity factor indicates that the annual power production represents only 14.4 % of the maximum theoretical power output that the turbine could produce if it operated at its rated capacity. This capacity factor is relatively low; wind turbines are not designed to operate at the maximum capacity factor.

The operating hours represent the expected number of hours per year that a turbine produces electricity. For all turbines except the Enercon E115, which has a lower cut-in speed of 2 m/s, the operating hours are 6700. The E−115 will have higher operating hours due to its ability to produce electricity in the wind speed zone between 2 and 3 m/s, which the other turbines cannot do because of their 3 m/s cut-in speed. This is evident from the wind distribution curves in Fig. 2 and wind speed histograms in Fig. 3. Although the E115 spins at 2 m/s, the power produced is insignificant at around 3 kW. However, noticeable power is produced at 3 m/s, nearly 58 kW, determined by analyzing the power curve of E115. A figure of 6693 yearly operating hours, roughly 77 % of the total 8760 h in a year, is reasonable and indicates that the wind resource in the Al-Jouf region is good enough to install large wind turbines with high utilization. Fig. 6 shows the total load hours, representing a turbine's yearly hours for a given capacity factor. The Vestas V126 has the highest number of total load hours, with 1259 full-load hours making up roughly 19 % of the total operating hours (6693 h). The Leitwind LTW101 has the lowest number of full load hours. The lower number of full load hours for the V126 is due to the low-frequency distribution of wind speed at 12 m/s and above, as shown in Figs. 2 and 3. The rated speed for the V126 is 12 m/s, at which the turbine produces a rated power of 3000 kW. Hence, the wind speed at the rated speed and above is rarely available, so total load hours and capacity factor are low. The same argument holds for the rest of the turbines, resulting in low capacity factor and full load hours.

The Vestas V126 turbine outperforms the other selected turbines in terms of yearly power production, capacity factor, and full load operating hours. Therefore, it is the optimal choice based on the Weibull distribution of wind speed for Al-Jouf. The V126 turbine's largest rotor diameter of 126 m among all other selected turbines produces the highest energy yield. This is because wind power is directly proportional to the rotor's swept area, as shown in Equation (7). According to our estimation, the V126 has the potential to produce 3779400 kWh/year, making it a good choice for building a utility-scale wind power plant in Al-Jouf. For example, a wind power plant with 100 V126 turbines can meet the energy demands of approximately 46000 individuals, given that energy consumption per capita in the Kingdom of Saudi Arabia is reported at 8239 kWh according to Saudi statistical data and world data on energy consumption for the year 2020 [49]. Our study findings also support the site selection for building a wind farm with strong wind resources, as estimated by the Weibull wind speed distribution over long-term historical data.

Moreover, our study suggests that installing large-capacity turbines will be more beneficial to build a utility-scale wind power plant with a high energy yield in this region. The Kingdom of Saudi Arabia has already planned a wind farm in this region with an installed capacity of 400 MW, comprising 99 turbines, each with a power output of 4.2 MW, which can reduce 988000 tons of $CO_2$ emissions per year. This will help to achieve the mission of sustainability and reduce global warming.

Our study results also support estimating wind power potential using Weibull distribution parameters. Additionally, the wind power calculator used is a practical, quick, and reliable tool to determine the power potential using Weibull parameters of wind distribution for a selected turbine. Therefore, our study is helpful for wind energy policymakers, planners, and governments to analyze the site's suitability and optimize the turbine selection without undergoing exhaustive efforts to provide an initial assessment.

## 4. Conclusion

The wind speed characteristics and wind power potential of Al-Jouf location was thoroughly examined in this study to determine its viability for wind energy. Weibull distribution function was employed to model the wind speed data for evaluating the wind properties and energy assessment. The model fitted well with the data predicted the wind behavior with good accuracy. Furthermore, a simple wind power calculator which is rarely reported was used to assess the wind power based on site conditions. Six widely used wind turbine types were selected to assess the energy yield and other turbine performance parameters to optimize the turbine selection for the site. This kind of study for Al-Jouf is hardly reported in literature. So, this study will be helpful for wind turbine manufacturers, developers, operators, and policymakers aiming to install large-capacity turbines in the Al-Jouf region. This research in general can guide wind energy policymakers, planners, auditors, governments, and small-scale users to assess site suitability, power production, and turbine selection by using this type of simple approach as a first step without undergoing exhaustive efforts.

The Weibull distribution function well fitted with the wind speed data, hence a useful statistical approach to accurately analyze the wind speed data and estimating power production at a site. The analysis demonstrated that an overall average wind speed at Al-Jouf was 4.38 m/s and average values of Weibull parameters, the shape parameter "k" and scale factor "c" were 1.98 and 4.86 m/s respectively. The value of k is approximately 2 that indicates a uniform and consistent wind distribution. These values of wind speed

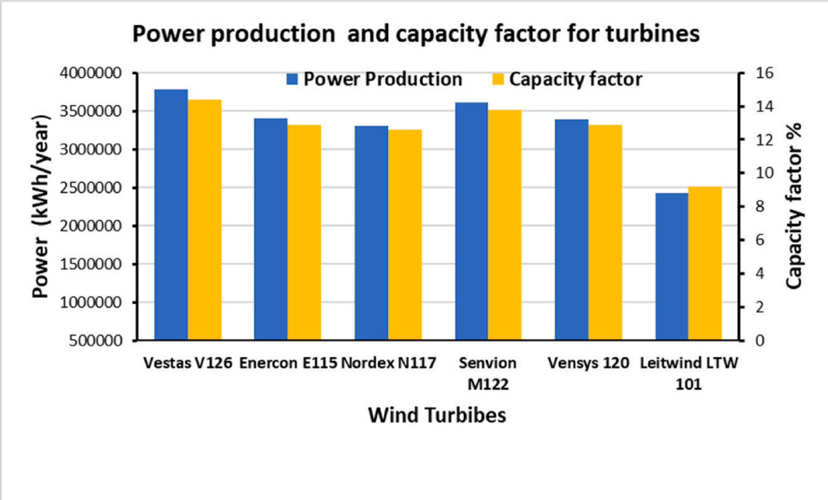


**Fig. 5.** Power generation and capacity factor of selected wind turbines for Al-Jouf.

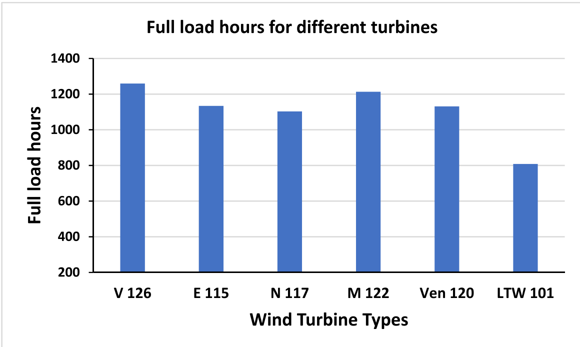


**Fig. 6.** Full load hours of selected wind turbines for Al-Jouf.

and Weibull parameters suggest that Al-Jouf has reliable and good wind resources. Vestas' V126 turbine outperformed other types of turbines with an annual energy yield of 3779400 kWh/year at a capacity factor of 14.4 %. The capacity factor is in a lower range due to the low frequency of wind speeds above 10 m/s at which the rated power is produced. Based on the estimated wind energy analysis, a wind farm of 100 wind turbines of type V126 can meet the energy demands of 46000 individuals approximately. These results are novel and promising to establish Al-Jouf as a suitable location for utility scale wind power projects.

### *4.1. Future work*

In the future work we aim to further identify the wind parameters in a holistic setting that can help to further optimize turbine selection for this region. Furthermore, a comprehensive techno-economic analysis will be conducted to assess the cost performance, optimize turbine selection, and determine the economic feasibility of the site. Exploring the use of more sophisticated machine learning methodologies for improved predictive modeling will augment the research in this domain. Subsequent studies in this domain could investigate the enhancement of wind energy systems by including energy storage options, such as batteries or hydrogen storage, to address the problem of intermittent power generation and improve the stability of the power grid.

## Data statement

Data included in article/supplementary material is referenced in the article.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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