

# **Statistical Analysis of Wind Speed Distribution for Energy Application in Saudi Arabia**

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## **Abstract**

This paper aimed to analyze the wind speed distribution and variability in Saudi Arabia with emphasis on the city of Riyadh using two different methodologies to estimate the Weibull scale and shape parameters: Weibull Least Squares and Weibull Openwind. Data collected from a local meteorological measurement data provided by King Abdullah City for Atomic and Renewable Energy (KACARE), over a period of one year were used to statistically analyze wind speed distributions. Results show that the agreement rate increases with the frequency of observations and the suitable heights for installing wind turbines machines in future applications were found to be 64.6 m and 79.8 m.

## **Keywords**

Wind energy, Riyadh, Weibull Parameters, and Wind Power Density.

## **1. Introduction**

In Saudi Arabia, more than 15% of the domestic oil production is used to generate electricity, and another 50% is consumed by electric power plants. KAPSARC reported (KAPSARC, 2018) that around 50% of the total electricity consumption in the building's stock comes from the energy consumption. In its vision 2030, Saudi Arabia set a target in its national transformation program on renewable energy and redirect the oil and gas exploration to other higher

value uses. Saudi Arabia significantly increased its renewable energy targets and long-term visibility. The Renewable Energy Project Development Office of Saudi Arabia's Ministry of Energy, Industry and Mineral Resources announced an increase in the renewable energy share to generate 40GW of solar energy and 16GW of wind power over the next decade. The revised five year-target was increased to a total capacity of 27.3GW with 20GW solar energy and 7.0GW wind energy by 2024, and a total of 58.7GW generated from solar and wind energy by 2030 (KSA, 2017a, 2017b, MEIM, 2019). In recent years, rapid growth has been seen in recognizing the benefits of wind energy as a key role in reducing greenhouse gas emissions, reducing dependence on oil, diversifying energy supply, and providing electricity at a low cost. According to various research and global energy status reports (Brahimi, 2019; GWEC, 2018), the global wind power capacity installed over the last ten years increased from around 159 gigawatts (GW) in 2009 to about 591 GW at the end of 2018. By the end of 2019, an installed capacity of around 656 GW is expected, as shown in Figure 1. With the current fast growth and development in wind generations, extensive research is needed into various areas, particularly wind speed distributions and power generation.

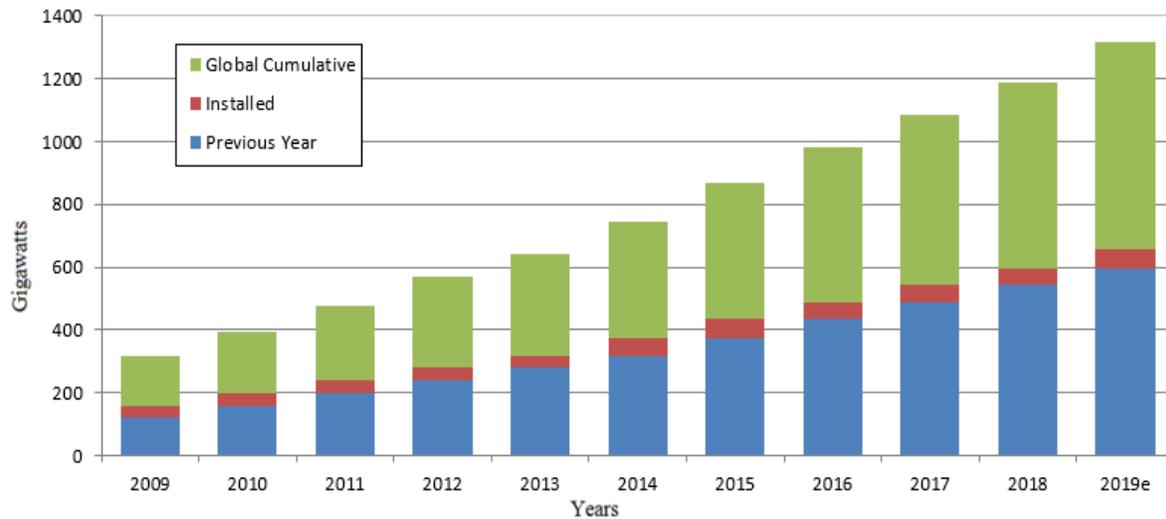


Figure 1: Global annual and cumulative installed wind energy capacity

Riyadh, city is the capital of Saudi Arabia it is located approximately 1,950 feet (600 meters) above sea level in eastern Najd, its geographical coordinates are 24° 38' 27" North, 46° 46' 22". The city's name is derived from the plural of the Arabic rawḍah, meaning gardens or meadows, so named for a natural fertility provided by its location at the juncture of Wadis Ḥanīfah and Al-Baṭḥā' ("History of Riyadh", 2020). The city is located in the Miṭṭaḥat Al-Riyāḍ, one of the country's 13 provinces, and is situated in the central portions of both the country and the larger Arabian Peninsula. Few of the world's cities have transformed as rapidly as Riyadh, which grew from a small, fortified desert village in the 17<sup>th</sup> century into a modern metropolis of several million inhabitants in the 20<sup>th</sup> century. Area city, 600 mi<sup>2</sup> (1,550 square km). Population of 5,188,286 in 2010, and 7,231,447 in 2020 (Kim, 2020: Wordpopulation, 2020).

The 2030 Saudi Arabia vision is a package of social and economic policies that are designed to reduce the kingdom's dependence on oil exports and to build a prosperous and sustainable economic future by focusing on the country's strength and policies(KSA, 2017a, 2017b). Part of the 2030 vision is the Renewable Energy Project Development Office (REPDO) by the Ministry of Energy that was established in 2017to deliver the goals of the National Renewable Energy Program (NREP). Working in collaboration with the Kingdom's energy sector stakeholders including the King Abdullah City for Atomic and Renewable Energy (K.A.CARE), The Electricity and Cogeneration Regulatory Authority (ECRA), and the Saudi Electricity Company (SEC), REPDO brings unified leadership to the Kingdom's capabilities in renewable energy research, measurement, data acquisition, regulation, pre-development and tendering ("Saudi Arabia Launches Round Three of National Renewable Energy Program", 2020). The main purpose of this paper is to investigate and statistically analyze wind speed distributions in Saudi Arabia a particular focus on Riyadh region.

## **2. Background**

With the main problem of greenhouse gas emissions, countries are now heading towards renewable energy (Gielen et al., 2019). It has been found that Saudi Arabia has a great potential in wind energy (Saleem & Ali, 2016), and to identify the optimal sites to place wind turbines for wind power generation, it is essential to know the wind distribution over those areas. Furthermore, the wind speed is important for wind scientists and engineers who study the way air moves, and pilots ("Anemometer", 2011). In addition to that, the wind speed is the most important parameter in the design and study of wind energy conversion systems (Al Buhairi, 2006). Al Buhairi used in his paper statistical methods to analyze the wind speed data of Taiz in the southwest of Yemen. He used the wind energy potential of the location is statistically analyzed based on wind speed data, measured over a period of four years. As the results of his study showed that the Weibull distribution is fitting the measured monthly probability density distributions better than the Rayleigh distribution for the whole years. And Weibull distribution provides better power density estimations than the Rayleigh distribution. Al Buhairi also mentioned in his results that the current technology does not provide economical electricity production from wind power and that the measurements should be evaluated in the long term in accordance with technological developments and reduction in the cost of turbines (Al Buhairi, 2006).

In their paper, Suomi and Vihma (2018), discussed the recent developments of wind gust measurement techniques based on turbulence measurements from research aircraft and from Doppler lidar that can potentially provide new information from heights and locations unreachable by traditional measurement techniques. The paper gave an overview of the history of the current status of anemometer from the perspective of wind gusts, it was mentioned that the fast-developing measurement methods based on Unmanned Aircraft Systems (UASs), which adds a better coverage of wind gust measurements in the future. Further, in the article, it was mentioned that different anemometer types and different formulas to calculate the wind gusts, which concluded the wind gusts had regional differences both in sampling and reporting practices. The overall accuracy of the measurements includes not only the accuracy of the anemometer system but also the environmental conditions. The changes in the environmental conditions surrounding the weather station may cause artificial changes in the measured wind gust climate (Suomi & Vihma, 2018). Further, in Brahimi's paper, (Brahimi, 2019) he proposed the use of artificial neural networks (ANNs) method as a means of predicting daily wind speed in a number of locations in the Kingdom of Saudi Arabia based on multiple local meteorological measurement data provided by K.A.CARE. In his study, it showed that it was possible to estimate and predict wind speed variability using ANN techniques. Based on different tests, ANN proved itself a flexible method in terms of accuracy and computer time usage, when compared to atmospheric models such as weather research and forecasting (WRF). As the best result was obtained with an RMSE of 0.6109 for ANN and an RMSE of 0.5543 for the random forest. Our tests also showed that 70%–30% for data training and testing provided the best correlation. (Brahimi, 2019)

## **3. Methodology**

### **3.1 Weibull Fit Algorithms**

We used two different methodologies to estimate the Weibull scale and shape parameters: Weibull Least Squares and Weibull Openwind.

The cumulative distribution function of the Weibull distribution:

$$F(U) = 1 - e^{-\left(\frac{U}{c}\right)^k}$$

Where U is the wind speed, c is the Weibull scale factor, and k is the Weibull shape factor. The shape parameter describes the width of wind speed data distribution, while the scale parameter indicates how 'windy' the considered location is (Fyrrippis et al., 2010):

The Weibull  $k$  value is the unitless shape factor from the Weibull distribution. This factor reflects the breadth of the distribution, with lower values corresponding to broader distributions while Weibull  $c$  value is the scale factor from the Weibull distribution. This factor is related to the average wind speed by the following equation:

$$U' = c G \left( \frac{1}{k} + 1 \right)$$

Where  $U'$  is the average wind speed,  $G$  is the gamma function, and  $k$  is the Weibull shape factor.

### 3.1.1 Weibull Least Squares:

Weibull Least Squares is a statistical procedure to find the best fit for a set of data points by minimizing the sum of the offsets or residuals of points from the plotted curve. can be described as the following:

$$\ln \left[ \ln \left[ \frac{1}{1 - F(U)} \right] \right] = k \ln U - k \ln c$$

### 3.1.2 Weibull Openwind:

In the Openwind algorithm for Weibull fitting, Weibull distribution is supposed to fulfill two criteria: First: The mean power density of the fitted Weibull distribution must match that of the observed wind speeds. Second: The mean wind speed of the fitted Weibull distribution must match that of the observed wind speeds (Lambert, 2017).

The mean wind power density of the Weibull distribution ( $WPD_{wbl}$ ) can be determined as follows, assuming constant air density:

$$WPD_{wbl} = \frac{1}{2} \rho A^3 G \left( \frac{3}{k} + 1 \right)$$

And the mean power density of the observed wind speeds ( $WPD_{obs}$ ), assuming constant air density also, can be calculated as follows:

$$WPD_{obs} = \frac{1}{2N} \rho \sum_{i=1}^N U_i^3$$

As the first requirement states that these two quantities must be equal, we can conclude that:

$$c^3 G \left( \frac{3}{k} + 1 \right) = \frac{1}{N} \sum_{i=1}^N U_i^3 \Rightarrow c = \sqrt[3]{\frac{\frac{1}{N} \sum_{i=1}^N U_i^3}{G \left( \frac{3}{k} + 1 \right)}}$$

The mean wind speed of the Weibull distribution ( $WPD_{wbl}$ ) can be determined as follows:

$$\bar{U}_{wbl} = c \Gamma \left( \frac{1}{k} + 1 \right)$$

And the mean of the observed wind speeds ( $U_{obs}$ ) can be calculated as follows:

$$\bar{U}_{obs} = \frac{1}{N} \sum_{i=1}^N U_i$$

Thus:

$$cG\left(\frac{1}{k} + 1\right) = \frac{1}{N} \sum_{i=1}^N U_i \Rightarrow c = \frac{\frac{1}{N} \sum_{i=1}^N U_i}{G\left(\frac{1}{k} + 1\right)}$$

Meaning that:

$$\sqrt[3]{\frac{\frac{1}{N} \sum_{i=1}^N U_i^3}{G\left(\frac{3}{k} + 1\right)}} = \frac{\frac{1}{N} \sum_{i=1}^N U_i}{G\left(\frac{1}{k} + 1\right)}$$

So, we will have only one unknown, which is k. When operating the Openwind Weibull fit algorithm, Windographer software first solves the last equation iteratively to find the k parameter. After that, it calculates the A parameter.

### 3.2 Wind Power Density

We calculated the wind power density, from the wind speed and air density using the following equation:

$$\frac{P}{A} = 0.5 \rho U^3$$

Where P is the wind power density or the power per unit area,  $\rho$  is the air density, A the swept area, and U is the average wind speed.

## 4. Results and Discussion

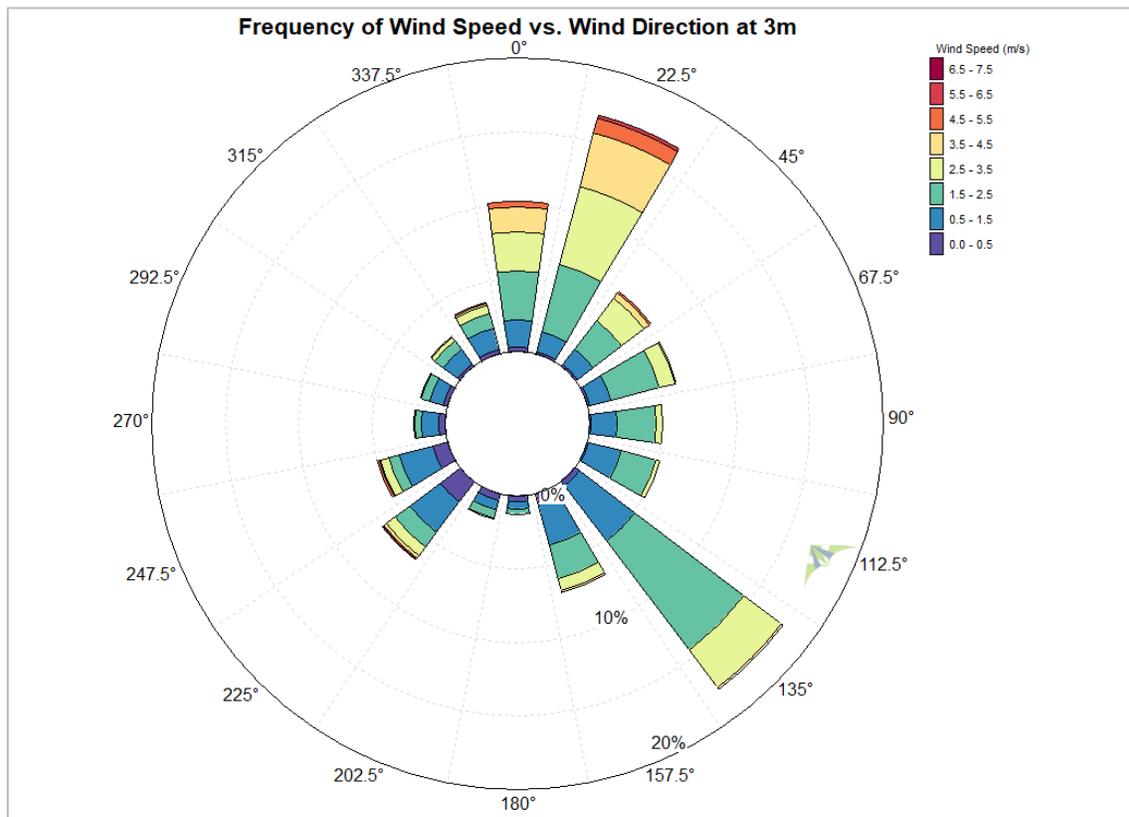


Figure 2: Wind speed and direction in Riyadh, 2015

In Figure 2, the plot is used to describe the distribution of wind direction and wind speed in Riyadh city . In order to know the wind speed frequency in the Riyadh region, we used windrose to show how the wind speed and direction are distributed, the data covers the year of 2015. The entire data available ranges from 2013 to 2016. The wind direction shows from the generated data that is mostly high in north, north-northeast, and southeast and it rarely blows from the northwest side.

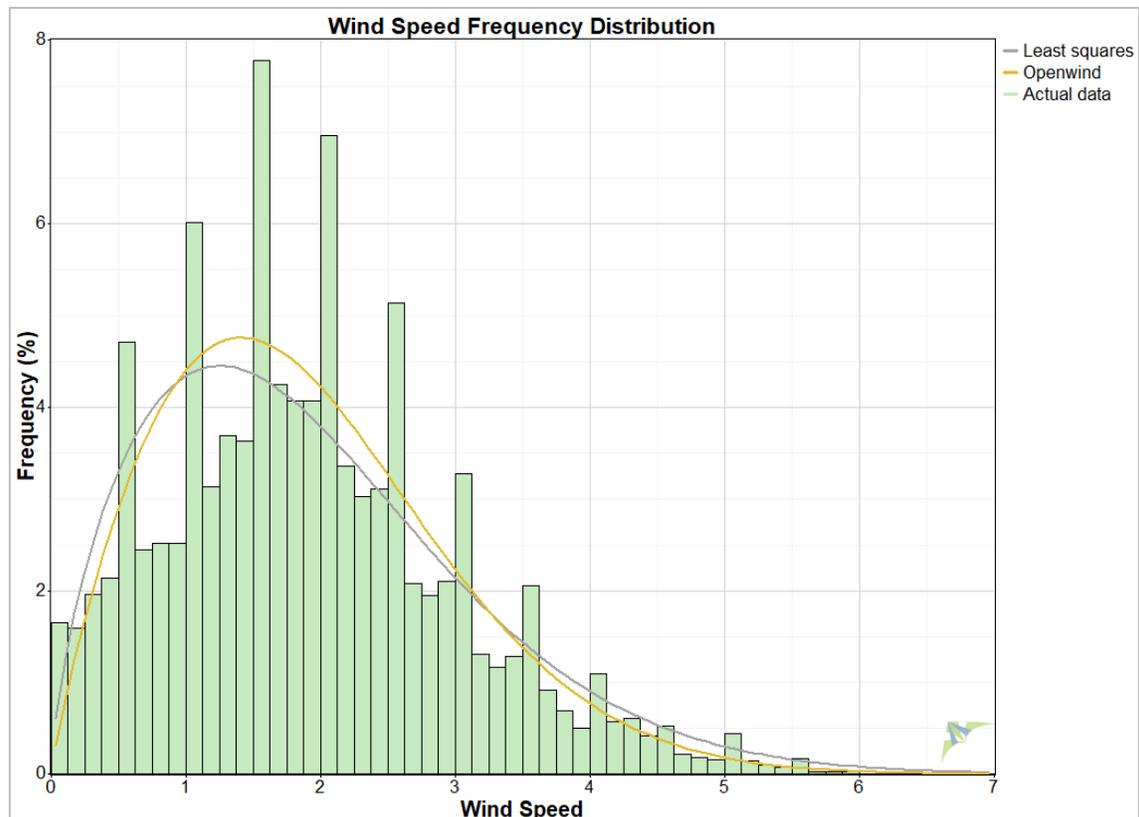


Figure 3: Wind Speed frequency distribution at 3 m

The average wind speed and frequency distribution of wind speed in Riyadh plotted in Figure 3 using Windographer software based on daily collected data for each hour in 2015. At the height of 3 m, the overall mean wind speed is 1.9 m/s. Weibull Least Squares approach results in 1.666 for k factor, 2.174 m/s for c factor and 10.6 W/m<sup>2</sup> for air density while Openwind approach results in 1.855 for k factor, 2.150 m/s for c factor and 8.8 W/m<sup>2</sup>. Based on that, any future wind turbine project should be built to be higher than 3 m.

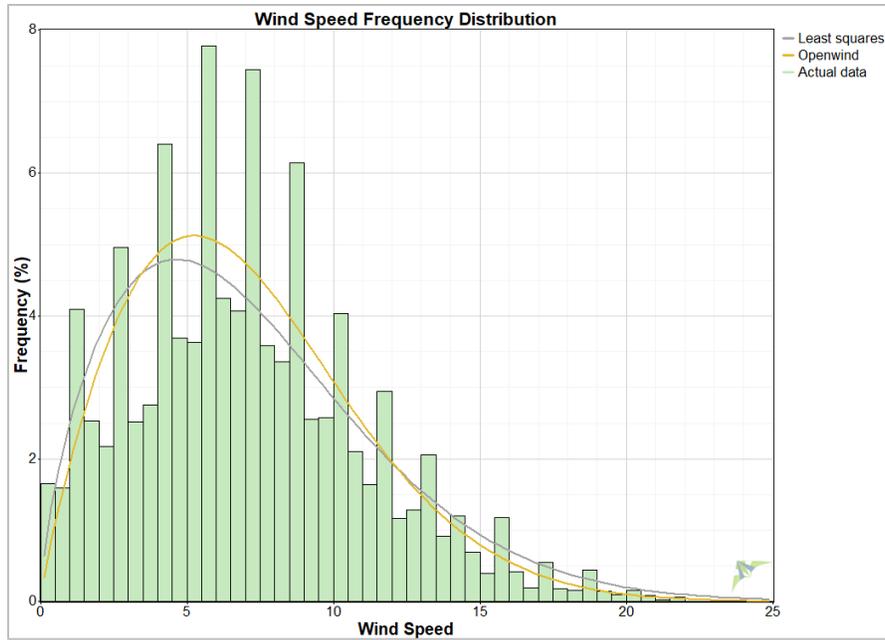


Figure 4: Wind Speed frequency distribution at 79.8576 m

As shown in Figure 4, at the height of 79.8576 m taking Vestas wind turbine's tower height as a reference, the overall mean wind speed is 7 m/s. Weibull Least Squares approach results in 1.666 for k factor, 8.078 m/s for c factor and 541.6 W/m<sup>2</sup> for air density while Openwind approach results in 1.854 for k factor, 7.988 m/s for c factor and 452.3 W/m<sup>2</sup> for air density.

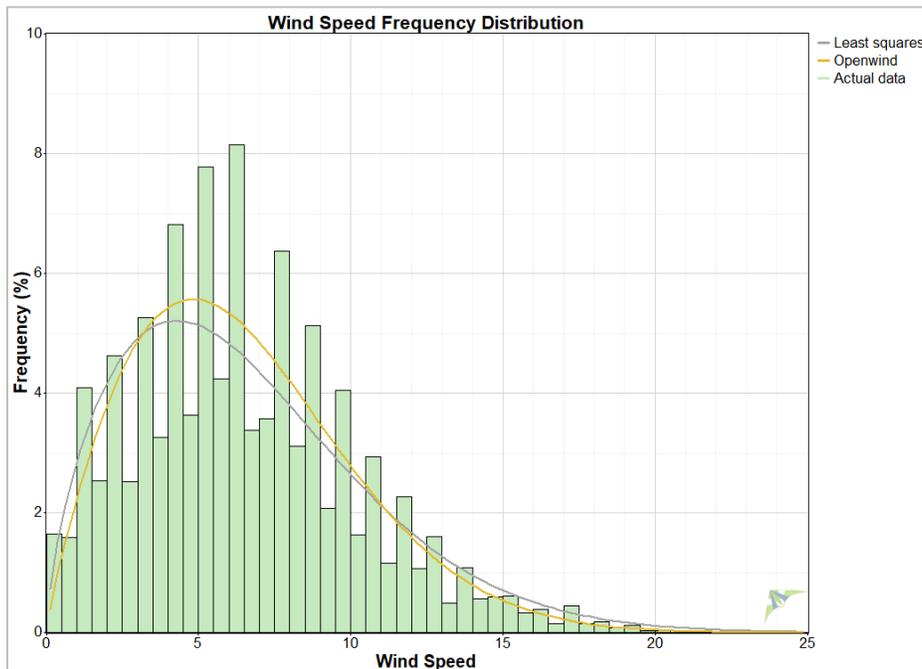


Figure 5: Wind Speed frequency distribution at 64.6176 m

As shown in Figure 5, at the height of 64.6176 m taking GE wind turbine's tower height as a reference, the overall mean wind speed is 6.5 m/s. Weibull Least Squares approach results in 1.666 for k factor, 7.422 m/s for c factor and

420.1 W/m<sup>2</sup> for air density while Openwind approach results in 1.854 for k factor, 7.339 m/s for c factor and 350.8 W/m<sup>2</sup> for air density.

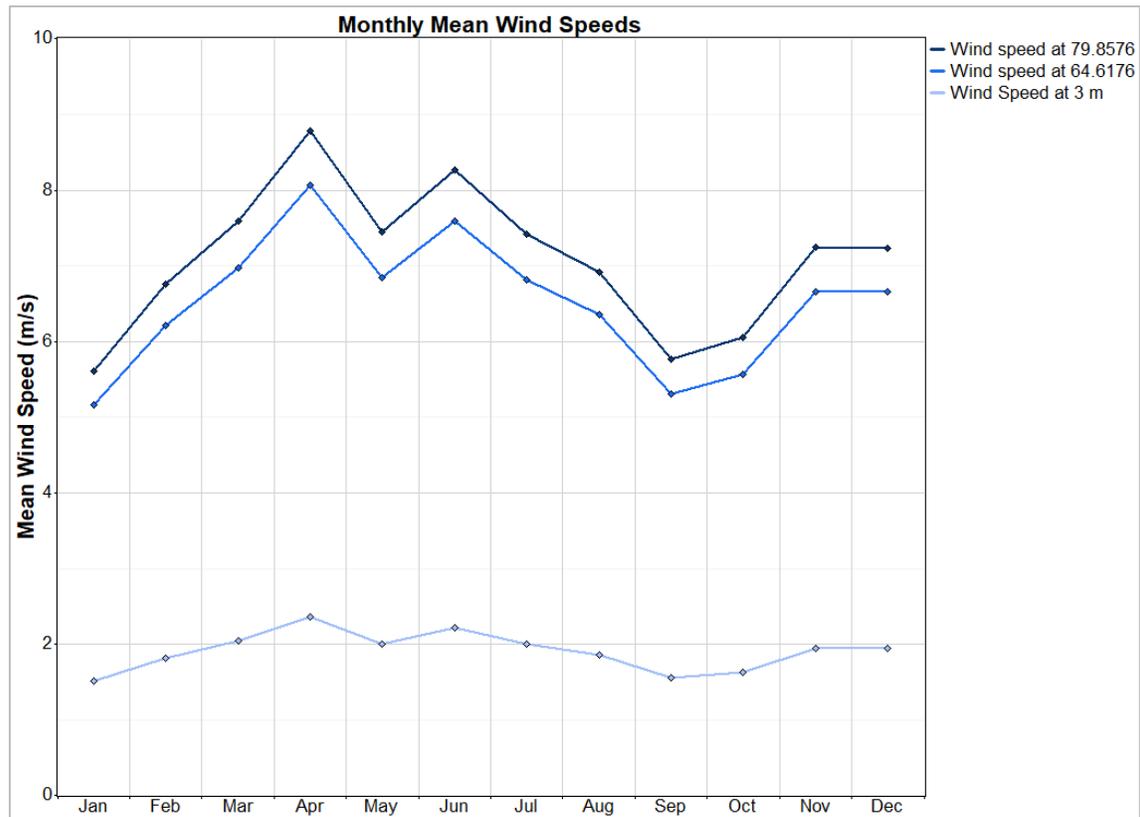


Figure 6: Monthly Mean Wind Speeds

From Figure 6 above, it is clear that the wind behavior in Riyadh, March to August the wind behavior is better than other months. Taking wind speed at 3 m as a reference, the maximum wind speed was calculated in April 8 m/s and 8.9 m/s for 79.8578 m and 64.6176 m respectively while the minimum wind speed was calculated in January 5.1 m/s and 5.7 m/s for 79.8578 m and 64.6176 m respectively which is higher than the cut-in speed of typical wind turbine shown in Figure 6 below that adapted from Wind Power program.

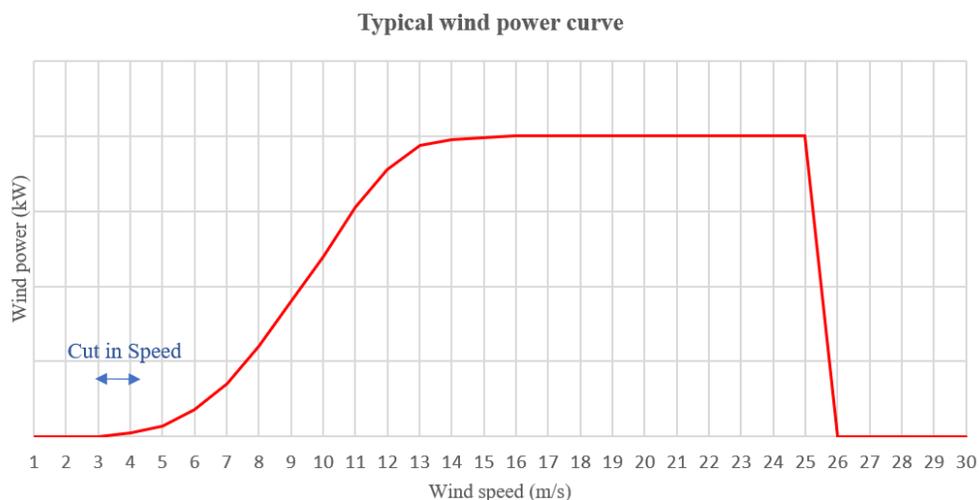


Figure 7: Typical wind power curve

## 5. Conclusion

This paper provides a strong background for possible future investment in wind energy in the region of Riyadh. Two mathematical methods for Weibull parameters estimation have been estimated numerically and graphically to simulate wind speed data obtained from measurement data provided by K.A.CARE. Results obtained using the two methods, namely the Weibull Least Squares and the Weibull Openwind compared quite well with the experimental data obtained from K.A.CARE. The use of Weibull distribution indicates that the region of Riyadh might be suitable for installing wind turbine machines. The monthly average wind speed and frequency distribution of wind speed in Riyadh has been plotted and analyzed for a possible deployment of wind power in Riyadh.

## Acknowledgments

This project is funded by Effat University with the Decisions No. UC#9/27 May. 2019/7.2-22e. The authors gratefully acknowledge the support provided by the College of Engineering at Effat University, Jeddah, Saudi Arabia.

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## **Biographies**

**Dr. Tayeb Brahimi**, Assistant Professor at the Department of Electrical and Computer Engineering (ECE), at Effat University, Jeddah, KSA, received his Ph.D. (1992) and Master's Degree (1987) from University of Montreal, Canada. He has worked as Research Scientist under Bombardier Chair/Canadair from 1992-1998. In 1998, he joined Jeppesen DataPlan in California, then Peregrine System as a Technical Support Analyst, Quality Assurance Engineer, and Consultant for Electronic data interchange (EDI) in Dallas, Texas. Dr. Tayeb Brahimi has been a consultant at IONPARA Inc. for wind energy and aeronautics. He published more than 80 articles in scientific journals, international conferences, on novel methodologies of teaching and learning, renewable energy, sustainability, and machine learning. Among other activities, he is a reviewer for many international journals, invited speaker by the Japan Society of Mechanical Engineering, the Gulf Educational Conference as well as the Int. Conference on Eng. Education & Research. He also participated in Public Debate on Energy organized by the Government of Quebec, Canada. Current research interest relates to renewable energy (solar, wind, wave, and waste to energy), sustainability, machine learning, use of technology to support learning, engineering education, MOOCs, and Makerspace. Other areas of interest include integrating innovative Islamic heritage into the STEM.

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