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Assessing Wind Power Potential at Sana'a and Amran in Yemen

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Abstract

In the field of electricity generation, one promising area is wind energy, since it is accessible and renewable worldwide. This study evaluated the wind power potential (WPP) at the selected locations (Sana'a and Amran). This study makes use of wind speed data that was recorded at a height of 10 meters over five years (2010–2014). The mean and maximum values of the recorded wind speeds are shown in this study. Analysis was done on the monthly, seasonal, and annual changes in wind speed. Weibull distribution function (WDF) has been used to examine the wind properties and power potential of the suggested locations. Using the real data that was recorded over the five years, the annual mean wind speeds (MWS) in Sana'a were determined to be 2.513, 2.6, 2.445, 2.462 and 2.6 m/s respectively and in Amran, they were determined to be 2.899, 2.656, 2.88, 2.945, 3.05 m/s respectively. The mean power and energy densities over the five years were found to be 8.207 W/m^2 and 71.889 kWh/m^2; 11.803 W/m^2 and 103.396 kWh/m^2 for Sana'a and Amran respectively. The power density (PD) determined using the WDF and the power density PD determined using actual wind data were almost identical. Based on the findings, the MWS at the two sites chosen for the study is less than 4.0 m/s, which is far slower than the cut-in wind speed of many wind turbines from modern models. So, we recommend that some studies should be conducted to evaluate the potential for wind energy at some sites in Sana'a and Amran governorates outside the cities especially in or near mountainous sites.

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1. INTRODUCTION

Public daily life, industry, and national progress all depend heavily on energy. Fossil fuels are the primary source of its production. Because fossil fuels have become more expensive due to expanding global energy consumption, the usage of renewable energy sources has been growing annually. Global renewable capacity is expected to grow by 2.7 times by 2030, surpassing countries' current ambitions by nearly 25%, but it still falls short of tripling. Considering existing policies and market conditions, our main case sees 5,500 gigawatts (GW) of new renewable capacity becoming operational by 2030 [1, 2]. The capacity of renewable energy has increased rapidly worldwide, with wind energy emerging as an important source as a result of declining costs and developments in technology. Renewable power capacity additions set a record in 2023 with 473 GW of new installed capacity a 54% increase compared to 2022 additions, and the largest annual growth since 2000. Total global renewables capacity in 2023 increased by 14% rate, from 3391 GW in 2022 to 3865 GW in 2023 [3].

Wind energy is the most important of these sources, and recent years have seen a sharp rise in investment in it. Wind energy has grown globally due to reduced costs and technological advancements. Cost reductions for onshore wind were driven by two key factors: wind turbine cost declines and capacity factor increase from turbine technology improvements [3]. Looking at this year's Global Wind Report, we can see strong progress by the wind industry in commissioning huge volumes of renewable energy [2, 4].

Although Yemen possesses a lot of wind energy, none of it has been utilized yet [5, 6].

The statistical evaluation and investigation of WEP is the most crucial first step in creating applications of wind energy. A small change in wind speed results in a large variation in the calculation of wind energy because the wind energy density changes with the third power of wind speed. It is therefore essential for accurately determining the wind speed at a certain site.

Using a variety of methodologies, numerous researchers from numerous nations have examined a region's WEP. The two approaches most frequently employed in WPP studies are Weibull distribution. Using a two-parameter Weibull function, Models of wind data have shown impressive accuracy for many years [7–9]. For instance, Studies in Nigeria, Indonesia, and Romania highlight the potential of wind energy in diverse geographic contexts [1, 10, 11]. The WEP in the Southern Jordanian region and in Ramallah, Palestine were evaluated in [12, 13].

Limited studies in Yemen have evaluated wind energy potential, focusing on areas like Socotra Island, and Al-Mokha which show promising wind speeds for turbine deployment [14–16]. Another study that was carried out used the WDF to investigate the WEP at Almukalla, Yemen [17]. In the first study of its type, Using the 2014 daily MWS dataset obtained at a height of 10 meters, five methods were employed to estimate the Weibull parameters of wind speed at Al-Hodeidah City in Yemen [18].

The potential for wind power and the economic feasibility of using wind turbines at Al-Hodeidah City to generate electricity were evaluated in our second study [19]. Numerous comparable evaluations have been conducted and assessed by [20–34].

For the two selected sites, no previously conducted studies have been done so far. Therefore, this study is considered a preliminary evaluation of WEP in Sana'a and Amran. By evaluating the wind characteristics, figuring out the available energy density, and calculating the amount of wind energy generated at different turbine heights, this study investigates the WEP of the study sites. It is based on the monthly dataset of wind speed for five years (2010-2014) collected at the two selected sites. The current study's findings are useful for Yemen's wind energy investments. The two selected cities Sana'a and Amran were chosen because they have lots of energy-requiring factories and wide agricultural lands.

The main aim of the current study is to assess the WPP of the selected sites to provide the community with exact information about wind.

This work is significant since Yemen is now experiencing a serious energy deficit and urgently needs innovative, reasonably priced energy sources that could lessen the suffering of the populace [6]. With a focus on the vast potential of renewable energy sources like wind and solar electricity, the Yemeni government is currently planning to increase its energy sources. The current study is therefore considered the first of this type for the selected sites. This study describes the wind conditions in the two chosen areas and gives investors in wind energy in the two regions accurate instructions.

2. SITE DESCRIPTION

The climate at Sana'a Airport is a highland desert, with moderate temperatures and little precipitation. Sana'a enjoys comparatively low temperatures in comparison to other places in Yemen because of its elevation, which is roughly 2200 meters or 7200 feet above sea level. Summers (June to August) can be hot during the day, with average highs of 25-30℃ (77-86℉), but cool at night. Winters (December to February) are warm, with average daytime temperatures of 15-20℃ (59-68℉) and overnight lows of 5-10℃ (41-50℉). Winter conditions in Sana'a are usually dry due to the city's relatively low humidity levels. Although there are notable day-to-night temperature changes, particularly during the winter, the climate is generally consistent throughout the year. In general, Sana'a experiences temperate temperatures and dry weather, which makes it distinct from Yemen's hotter coastal regions. Amran's climate is somewhat similar to Sana'a's, but it has unique features of its own because of its geographical location and elevation, which causes temperatures there to be lower than in many other places of Yemen. During the day, summer temperatures can rise to about 25-30℃ (77-86℉), but at night, particularly in the winter, they can drop considerably. Wintertime highs can drop as low as 2 to 5 ℃ (36 to 41 ℉), but midday highs usually fall between 15 and 20℃ (59 and 68 ℉). Amran has comparatively low humidity, much like Sana'a, though it can rise during the rainy season.

Especially during the winter, there might be a noticeable difference in temperature between day and night. In contrast to Yemen's hotter coastal areas, the summer months are typically temperate and pleasant. Amran is one of Yemen's more temperate climates, with generally milder temperatures, moderate precipitation, and notable day-to-night temperature variations. The Yemen Civil Aviation and Meteorological Authority recorded wind data at the proposed sites at a height of 10 m for five years, from January 2010 to December 2014, measuring monthly MWS and monthly maximum wind speeds. The meteorological station coordinates for this study are shown in Table 1.

3. METHODOLOGY

To easily evaluate the feasibility of energy generation and its economic feasibility, the energy density and wind speed distribution, frequencies, and directions for the two chosen regions must be evaluated. These methods

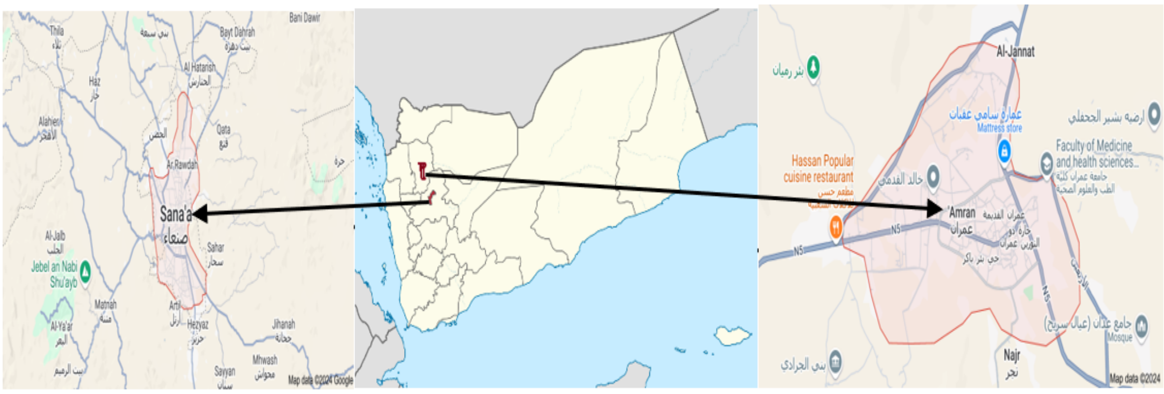

Figure 1. Map of Yemen and the location of Sana'a and Amran governorates.

Table 1. Geographical coordinates for the study regions.

Variable	Sana'a (Sana'a airport)	Amran (Raydah, Ar Rub' Ash Sharqi)
Latitude	15:31′ N	15:46′ N
Longitude	44:11′ E	44:01′ E
Elevation	2190 m above the sea level	2208 m above sea level
Anemometer height	10 m above the ground level	10 m above the ground level

Table 2. Specifications of meteorological sensors.

City	Sana'a	Amran
Type	3-Cup anemometer	3-Cup anemometer
Compony	Thies	Casella
Serial #	308098	0453533
Height	10	10

will be thoroughly covered to investigate wind speed at the study locations.

3.1. WEIBULL DISTRIBUTION FUNCTION

An important initial step in assessing the WEP is to estimate the wind speed probability distribution function (PDF). Alternatively, it is possible to predict the effectiveness of wind energy systems at a particular site by using the wind speed PDF. One of the PDFs was selected for the case study because of its accurate and adequate calculation of wind energy potential as well as its analysis and interpretation of wind speed distribution.

The WDF is the most suitable wind speed PDF. The probability density function and the cumulative distribution function of wind speeds can be given as follows [18, 35]:

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{1}$$

$$F(v) = 1 - \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{2}$$

where v is the wind speed, k and c are the shape and scale Weibull parameters respectively which can be related to the MWS V_m and standard deviation σ as follows [36]:

$$k = \left(\frac{\sigma}{V_m}\right)^{-1.086} \tag{3}$$

$$c = \left(\frac{V_m}{\Gamma\left(1+\frac{1}{k}\right)}\right) \tag{4}$$

Two more essential wind speed indicators, the maximum energy carrying wind speed (MECWS) indicated by V_{maxE} and the most probable wind speed (MPWS) indicated by V_{mp}, are calculated using Weibull parameters. The V_{maxE} is important when considering the existence of wind turbines at a specific site, whereas the V_{mp} represents the wind speed that occurs most frequently in a given distribution.

The V_{maxE} and V_{mp} can be given by the following formulas [19, 37] once shape and scale parameters have been calculated:

$$V_{mp} = c\left(1 - \frac{1}{k}\right)^{\frac{1}{k}} \tag{5}$$

$$V_{maxE} = c\left(1 + \frac{2}{k}\right)^{\frac{1}{k}} \tag{6}$$

3.2. WIND POWER DENSITY

Given that wind power is proportional to the cube of wind speed. Wind power $P(W)$ can be expressed in terms of air density $\rho\ (kg/m^3)$, turbine blade swept area $A_T\ (m^2)$, and a set of wind speed data $v_i\ (m/s)$ as follows [35]:

$$P = \frac{1}{2}\rho\, A_T\, \frac{1}{n}\left(\sum_{i=1}^{n} v_i^3\right) = \frac{1}{2}\rho\, A_T\, v_{rmc}^3 \tag{7}$$

The wind turbine area has no effect on the WPD, which can be calculated using,

$$WPD = \frac{P}{A_T} = \frac{1}{2}\rho\, v_{rmc}^3 \tag{8}$$

The ED is determined using real-time-series data and is provided by

$$WED = \frac{1}{2}\rho v_{rmc}^{3} T \tag{9}$$

Both the available wind energy and the operational features of the wind energy abstraction device determine how much power may be generated from the wind [35]. After Betz proved that wind turbines could not generate all of their power, a limit known as the Betz limit—represented by the symbol C_p was established. The Betz limit's maximum efficiency is 59.3% (0.593).

The most significant wind indicator is the WPD, which quantifies the energy produced by fluctuating wind speeds at a specific location. The predicted monthly or annual WPD per unit area of a site can be performed using the WDF parameters (k, c) [35, 38]:

$$P_W = \frac{1}{2}\rho c^3 \Gamma\left(1+\frac{3}{k}\right)\left(\frac{W}{m^2}\right), \tag{10}$$

where ρ represents air density which is considered at Sana'a and Amran to be $0.964\, kg/m^3$ and $0.962\, kg/m^3$, respectively. The theoretical wind energy per unit area for a certain time T can be found using the WDF as follows:

$$E_W = \frac{1}{2}\rho c^3 \Gamma\left(1+\frac{3}{k}\right) T. \tag{11}$$

3.3. VARIATION WITH HEIGHT

It is possible to determine the wind speed at various heights by extrapolating the measured wind speed when data energy for extrapolating wind speed data at different heights, is thought to be a useful tool. It can be expressed as is collected at different elevations. The power law is the most straightforward method for extrapolating the wind, though there are other approaches as well. This law, which is widely used to evaluate the WEP [35]:

$$\frac{v}{v_0} = \left(\frac{Z}{Z_0}\right)^{\alpha}, \tag{12}$$

where α is the wind shear exponent, v_0 is the wind speed at the reference height Z_0, and v represents the wind speed at the equivalent height Z. The shear exponent changes with ground texture and is dependent on surface topology. A typical value of α for flat terrain and low roughness surfaces is $1/7$, which is regarded as a constant. Exponent α values range from less than 0.1 for water, ice surfaces, or extremely flat terrain to more than 0.25 for forests and woodlands [35]. The value of α was taken to be $1/7$ for this work. The corresponding parameters c_Z and k_Z at a specified height, Z can be calculated given the Weibull parameters c_0 and k_0 at the reference height Z_0 by the following equation [19]

$$c_Z = c_0 \left(\frac{Z}{Z_0}\right)^{\beta} \tag{13}$$

Moreover,

$$k_Z = k_0 \frac{1-0.088\ln\left(\frac{Z_0}{10}\right)}{1-0.088\ln\left(\frac{Z}{10}\right)} \tag{14}$$

The exponent β can be given by

$$\beta = \frac{0.37-0.088\ln(c_0)}{1-0.088\ln(Z/10)} \tag{15}$$

3.4. ERROR ANALYSIS

Before the measured parameters can be examined, the Weibull parameters that were previously mentioned must be verified using a criterion. Several statistical methods can be used to calculate errors and then evaluate them to determine the most efficient method for these calculations. Four performance indicators are used to compare the performance of the seven Weibull methods stated above statistically: RMSE, chisquare test (χ^2), correlation coefficient (R), and determent coefficient (R^2) which are calculated using Eqs.(16-19)

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2} \tag{16}$$

$$\chi^2 = \sum_{i=1}^{n}\frac{(y_i - x_i)^2}{x_i} \tag{17}$$

$$R = \frac{\sum_{i=1}^{n}(x_i-\bar{x})\cdot(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2\cdot\sum_{i=1}^{n}(y_i-\bar{y})^2}} \tag{18}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - x_i)^2}{\sum_{i=1}^{n}(y_i-\bar{y})^2} \tag{19}$$

where, x_i and y_i, in equations (16) through (19), are the predicted probability values, using the WDF, and the actual probability values, respectively. The $\bar{x}$ and $\bar{y}$ are the probabilities of average predicted and actual wind speed values, respectively, and n represents the size of the wind speed dataset.

4. RESULTS AND DISCUSSION

This study evaluated mean monthly wind speed data from 2010 to 2014. It was gathered at a height of $10\,m$ at Sana'a Airport and Amran (Raydah, Ar Rub' Ash Sharqi) in Yemen. The wind speed probability distribution was investigated using the WDF. Utilizing statistical characteristics such as the MWS, the output PD and ED were computed. Wind directions were investigated to generate the most accurate evaluation of the relevant wind field. The following section discusses the findings.

4.1. WIND SPEED ANALYSIS

Figure 2 shows the monthly MWSs during the year for the five years, 2010 to 2014 in Sana'a, for 12 months (monthly change); the monthly MWSs of the five years display a consistent pattern over the 12 months. Higher wind speeds were noticed in August of the year in 2014, Jul of the year 2011, Jul of the year 2013 and Jul for the mean of the five years. The wind speed varies from a maximum of 3.09 m/s in August of the year 2014 to a minimum of 1.71 m/s in Jan of the year 2010. Figure 2 shows that the MWS for the year is quite consistent, ranging between 2.3 and 2.7 m/s, and it was a little higher in 2014 than in the other four years.

Figure 3 shows the monthly MWSs during the year for the five years, 2010 to 2014 in Amran, for 12 months (monthly change); the monthly MWSs of the five years show a consistent pattern during the 12 months. Higher wind speeds were noticed in March of the year 2010, August of the year 2014, Jul of the year 2013 and March for the mean of the five years. The wind speed varies from a maximum of 3.913 m/s in March of the year in 2010 to a minimum of 2.52 m/s in November of the year 2011. Figure 3 shows that the mean wind speed for the year is quite consistent, ranging between 2.7 and 2.9 m/s, and it was a little higher in 2014 than in the other four years.

Figure 4 displays the five-year seasonal MWS together with its mean for the first site Sana'a Airport. The Winter (December–February), spring (Mar.–May), summer (Jun.–Aug.), and autumn (Sep.–Nov.) are the four seasons that form the whole year. For the five years, summer is the best season; the highest recorded wind speeds were 2.96, 2.712, and 2.67 m/s in 2010, 2011, and 2014, respectively. Spring and autumn are the next most favorable seasons. Winter has the smallest wind speeds out of the three seasons (about 2.12 m/s).

Figure 5 displays the five-year seasonal MWS together with its mean for the second proposed site (Amran). With the highest recorded wind speeds of 3.125, 3.58, and 2.95 m/s in 2014, 2013, and 2010, respectively, summer is the best season for the five years. The next best seasons are autumn and spring. Winter has the lowest wind speed of the three seasons (about 2.83 m/s).

4.2. WEIBULL DISTRIBUTION ANALYSIS

Tables 3 and 4 provide a summary of the site's monthly and yearly MWSs, Weibull parameters (k and c) determined utilizing Eqs. (3) and (4), and some wind characteristics like the MPWS (V_{mp}) and the MECWS (V_{maxE}) over the five years in Sana'a and Amran respectively.

Tables 5 and 6 display seasonal data in Sana'a and Amran respectively. The shape parameter had an average value of 7.019 and 5.018 during the five years for Sana'a and Amran respectively. The average shape parameter in the five years reached its highest value of 9.407 in December and 6.282 in April, and also its lowest value of 5.205 in Feb and 3.878 in July in Sana'a and Amran respectively. For the five years, the mean-scale parameter was 2.699 m/s and 3.145 m/s for Sana'a and Amran respectively. The highest average scale parameter was 3.179 m/s in Jul and 3.452 m/s in Mar, while the lowest scale parameter was noticed to be 2.128 m/s in Dec and 2.974 m/s in April in Sana'a and Amran respectively. The MPWS for the five years was calculated to be 2.64 m/s and 2.998 m/s; the range of V_{mp} values was 2.089 to 3.131 and 2.888 to 3.325 m/s for the two sites Sana'a and Amran respectively. For the five years, 2.797 and 3.378 m/s were estimated to be the mean MECWS, that is fluctuated between 2.173 to 3.262 m/s and between 3.107 to 3.679 m/s for Sana'a and Amran respectively.

The seasonal shape parameter k had a maximum value of 3.808 in summer and 5.3 in autumn and also a minimum value of 3.238 in winter and 4.614 in summer for the two sites Sana'a and Amran respectively. The estimated seasonal scale parameter c fluctuated from 2.365 m/s in winter to 3.262 m/s in summer and from 3.082 m/s to 3.217 m/s in summer for the two selected sites Sana'a and Amran respectively.

Tables 5 and 6 show that seasonal V_{mp} values ranged from 2.042 to 3.006 m/s in Sana'a, and from 2.942 m/s to 3.05 m/s in Amran. In addition, the highest and the lowest seasonal values of V_{maxE} for Sana'a were 3.65 m/s in summer and 2.835 m/s in winter and for Amran they were 3.508 m/s in summer and 3.286 m/s in autumn.

Table 3. Monthly and yearly MWS, Weibull parameters, MPWS, and MECWS for 2010- 2014 in Sana'a.

month	V_m	SD	k	c (m/s)	V_{mp} (m/s)	V_{maxE} (m/s)
Jan	2.001	0.425	5.383	2.170	2.089	2.301
Feb	2.336	0.511	5.205	2.538	2.436	2.701
Mar	2.548	0.492	5.964	2.747	2.664	2.884
Apr	2.486	0.361	8.119	2.638	2.595	2.710
May	2.775	0.536	5.966	2.992	2.902	3.141
Jun	2.907	0.484	7.006	3.107	3.040	3.220
Jul	3.000	0.425	8.359	3.179	3.131	3.262
Aug	2.937	0.426	8.148	3.116	3.067	3.201
Sep	2.669	0.411	7.627	2.841	2.789	2.929
Oct	2.492	0.389	7.509	2.655	2.605	2.739
Nov	2.128	0.321	7.810	2.263	2.223	2.330
Dec	2.020	0.256	9.407	2.128	2.103	2.173
Year	2.525	0.420	7.019	2.699	2.640	2.797

Figures 6 and 7, illustrate a comparison of the Weibull probability density function and cumulative density function with actual data histograms for the two selected sites Sana'a and Amran respectively. Eq. (3) was used to calculate the Weibull parameter k, which was found to vary throughout the five years between 5.2 and 9.407 in Sana'a and between 3.878 to 5.98 in Amran. This pattern can be seen in the related figures. Eqs.(16–19) were used to calculate the errors, and the accuracy of the results based on the WDF was examined. The errors (RMSE, χ^2, R^2, and MAPE) are listed in Table 7.

All these error values are determined to be within an

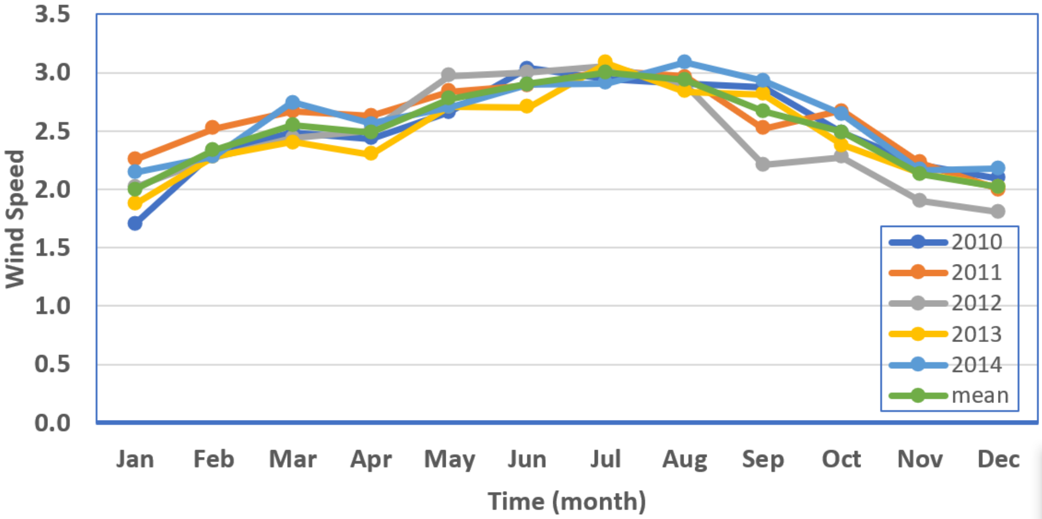

Figure 2. Variations in monthly MWS during the year 2010-2014 in Sana'a.

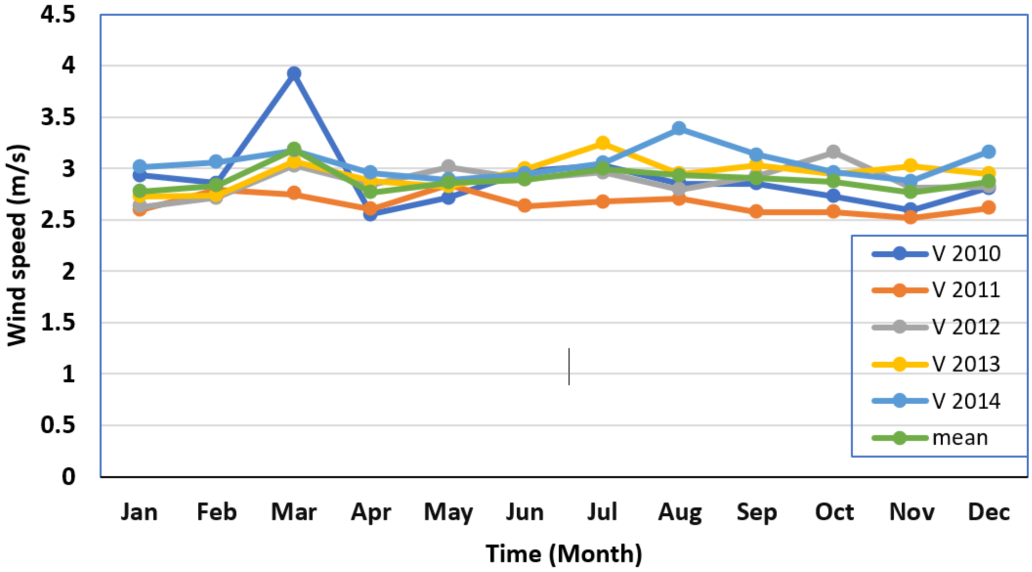

Figure 3. Variations in monthly MWS for 2010-2014 in Amran.

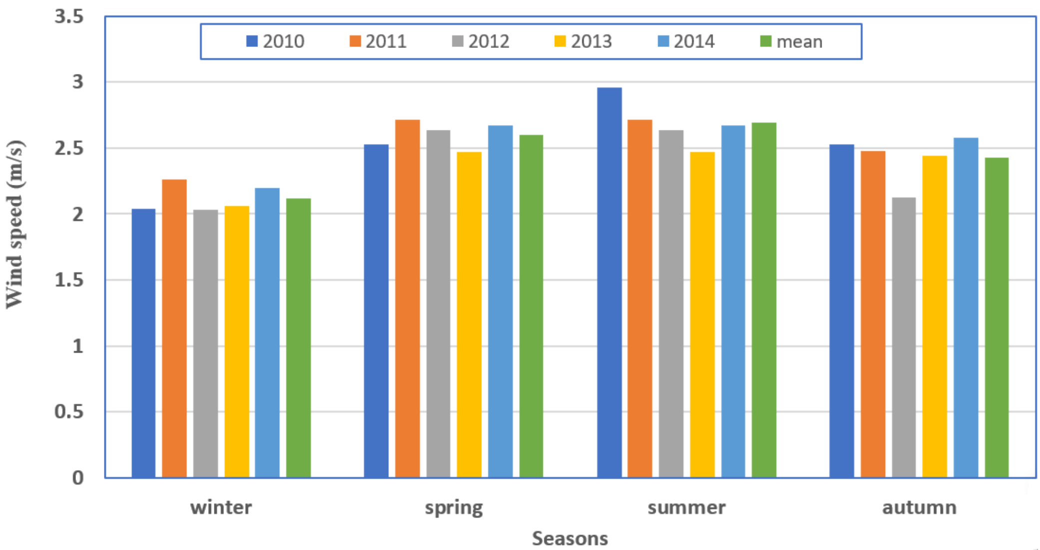

Figure 4. Seasonal-MWS variations for the years (2010-2014) in Sana'a.

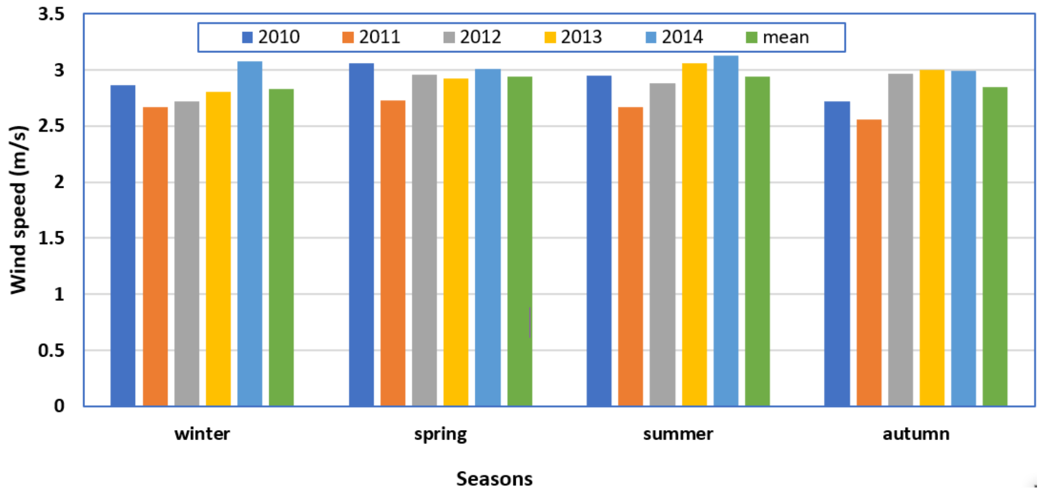

Figure 5. Variations in Seasonal-MWSs for the years (2010-2014) in Amran.

Table 4. Monthly and yearly MWS, Weibull parameters, MPWS, and MECWS for 2010- 2014 in Amran.

month	V_m	*SD*	*k*	*c (m/s)*	V_{mp} (m/s)	V_{maxE} (m/s)
Jan	2.777	0.652	4.824	3.031	2.888	3.257
Feb	2.831	0.657	4.890	3.088	2.947	3.312
Mar	3.185	0.668	5.453	3.452	3.326	3.655
Apr	2.766	0.509	6.283	2.974	2.893	3.108
May	2.856	0.791	4.032	3.149	2.934	3.480
Jun	2.886	0.808	3.983	3.185	2.962	3.527
Jul	2.990	0.858	3.878	3.305	3.060	3.679
Aug	2.934	0.565	5.980	3.163	3.068	3.320
Sep	2.903	0.618	5.367	3.149	3.031	3.341
Oct	2.870	0.679	4.782	3.133	2.983	3.371
Nov	2.765	0.552	5.751	2.988	2.890	3.147
Dec	2.871	0.653	4.990	3.127	2.990	3.346
Year	2.886	0.243	5.018	3.145	2.998	3.378

Table 5. Seasonal-MWS, Weibull parameters, MPWS, and MECWS for 2010- 2014 in Sana'a.

Season	V_m	*k*	*c* (m/s)	V_{mp} (m/s)	V_{maxE} (m/s)
Winter	2.119	3.238	2.365	2.042	2.835
Spring	2.603	3.247	2.905	2.569	3.400
Summer	2.948	3.808	3.262	3.006	3.650
Autumn	2.430	3.716	2.692	2.474	3.024

acceptable range for the two selected sites, confirming the better fit of the WDF. Although the data collected suggested that the most likely wind speed would be closer to 3 m/s, the WDF expected that it would be 3 m/s for five years, despite minor errors.

Although the observed data suggested that the most likely wind speed would be closer to 3 m/s, the WDF predicted that it would be 3 m/s for five years, despite minor mistakes.

4.3. WIND SPEED EXTRAPOLATION

Real wind turbines are set up at different elevations, greater than $10m$ above ground level (AGL), because wind speed changes with altitude. Eq. (12) is also used to determine the annual MWSs at various elevations (10, 30, and 50 m) to determine the optimal height for the wind turbines. This is the first step in using the data to analyze and calculate the wind power in the specified area.

Table 6. Seasonal-MWS, Weibull parameters, MPWS, and MECWS for 2010- 2014 in Amran.

Season	V_m	*k*	*c* (m/s)	V_{mp} (m/s)	V_{maxE} (m/s)
Winter	2.826	4.902	3.082	2.942	3.305
Spring	2.936	5.256	3.192	3.051	3.414
summer	2.937	4.614	3.218	3.030	3.509
Autumn	2.846	5.300	3.090	2.968	3.286

Table 7. Analysis of WDF errors.

Sites	RMSE	χ^2	R	R^2	MAPE
Sana'a	0.0673	0.0473	0.9082	0.9661	0.0537
Amran	0.234	0.6112	0.9823	0.9236	0.2094

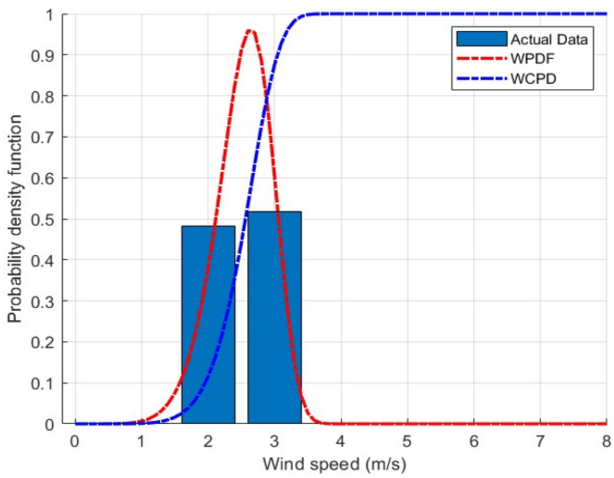

Figure 6. Analysis of the frequency distribution of wind speed for 2010-2014 in Sana'a.

For the first selected site (Sana'a Airport), Fig. 8 shows that, for the five years, the yearly MWSs were 2.525 m/s, 2.954 m/s, and 3.177 m/s, and the values of the mean shape parameter were 3.41, 3.775 and 3.973,

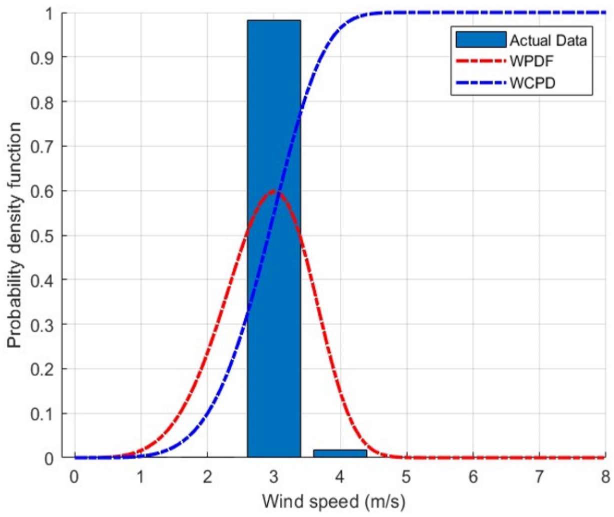

Figure 7. An investigation of wind speed's frequency distribution in Amran from 2010 to 2014.

also the values of the mean scale parameter were 2.81 m/s, 3.946 m/s and 4.742 m/s at the three heights 10 m, 30 m, and 50 m respectively. Similarly, For the second selected site (Amran), Fig. 9 shows that, for the five years, the yearly MWSs were 2.89 m/s, 3.37 m/s, and 3.62 m/s, and the values of the yearly mean shape parameter were 5.02, 5.55 and 5.85, also the values of the yearly mean scale parameter were 3.15 m/s, 4.36 m/s and 5.21 m/s at the three heights 10 m, 30 m, and 50 m respectively.

4.4. WIND POWER DENSITY AND ENERGY

It is crucial to discuss the WPD and WED produced. The average air density is $0.964\,kg/m^3$ at the first study site (Sana'a) and $0.962\,kg/m^3$ at the second study site (Amran). The monthly and annual mean PD and ED changes were calculated using the measured data in conjunction with the Weibull parameters in Amran and Sana'a, respectively, as shown in Tables 8 and 9.

Table 8. Monthly, mean measured, Weibull wind PD and ED and annual mean in Sana'a.

Month	PD (W/m^2) measured	ED/ (kWh/m^2) measured	PD_W (W/m^2)	ED_W (kWh/m^2)
Jan	3.965	2.950	5.894	4.385
Feb	6.165	4.143	9.597	6.449
Mar	8.031	5.975	11.409	8.488
Apr	7.442	5.358	9.174	6.605
May	10.342	7.695	14.735	10.963
Jun	11.879	8.553	15.579	11.217
Jul	12.757	9.491	15.965	11.878
Aug	12.234	9.102	15.116	11.246
Sep	9.433	6.792	11.634	8.376
Oct	7.536	5.607	9.529	7.090
Nov	4.685	3.373	5.843	4.207
Dec	4.009	2.983	4.690	3.489
Year	8.207	71.889	10.764	94.290

In the WDFs of months with low wind speeds, the PD is somewhat understated. This conclusion is demonstrated in Tables 8 and 9, which yielded nearly identical results. It was determined that for the five years 2010- 2014, the annual mean PDs were $8.207\,W/m^2$, and $11.803\,W/m^2$, while the annual mean EDs were $71.889\,kWh/m^2$, and $103.396\,kWh/m^2$ for Sana'a and Amran respectively, based on real data. The monthly maximum mean PD was $12.757\,W/m^2$ in Jul in Sana'a and $16.284\,W/m^2$ in March in Amran. The lowest monthly average PDs were measured to be 3.965 in Jan and 10.29 in April in Sana'a and Amran respectively. The months stated above also had the lowest and highest energy density readings during the five years. At a height of 10 meters, these outputs were scaled using the wind classification, which indicates that the two chosen locations, Sana'a and Amran, are in Class 1 and should not be used for the installation of small wind turbines [39]. Figures 10 and 11 illustrate how Sana'a's and Amran's summertime wind speeds led to a higher WPD over the five years, which was determined to be more than $15\,W/m^2$ in Sana'a and more than $25\,W/m^2$ in Amran. According to calculations, all seasons in the two locations are in Power Class 1 on the standard wind power scale, which has a PD of less than $100\,W/m^2$ throughout the five years.

Table 9. Monthly, mean measured, Weibull wind PD and ED and annual mean in Amran.

Month	PD (W/m^2) measured	ED/ (kWh/m^2) measured	PD_W (W/m^2)	ED_W (kWh/m^2)
Jan	10.425	7.756	12.015	8.939
Feb	10.995	7.389	12.688	8.526
Mar	16.284	12.115	17.599	13.093
Apr	10.290	7.408	11.218	8.077
May	11.251	8.371	13.799	10.267
Jun	11.645	8.384	14.307	10.301
Jul	13.013	9.682	16.066	11.953
Aug	12.414	9.236	13.510	10.051
Sep	11.934	8.592	13.378	9.632
Oct	11.545	8.589	13.285	9.884
Nov	10.318	7.429	11.394	8.204
Dec	11.526	8.575	13.158	9.790
Year	11.803	103.396	13.535	118.563

5. CONCLUSION

The main output of the study was the average seasonal wind speed in Sana'a and Amran. The paper carefully studied the wind speed distribution and wind power densities (WPDs) over these two locations in Yemen, using average monthly wind data from 2010 to 2014 and Weibull statistics. For Sana'a, the MPWS and MECWS were found to be 2.64 m/s and 2.797 m/s, respectively, while for Amran, they were 2.997 m/s and 3.378 m/s. Analysis of wind speed and power distribution over the year reveals that wind speeds and power densities are

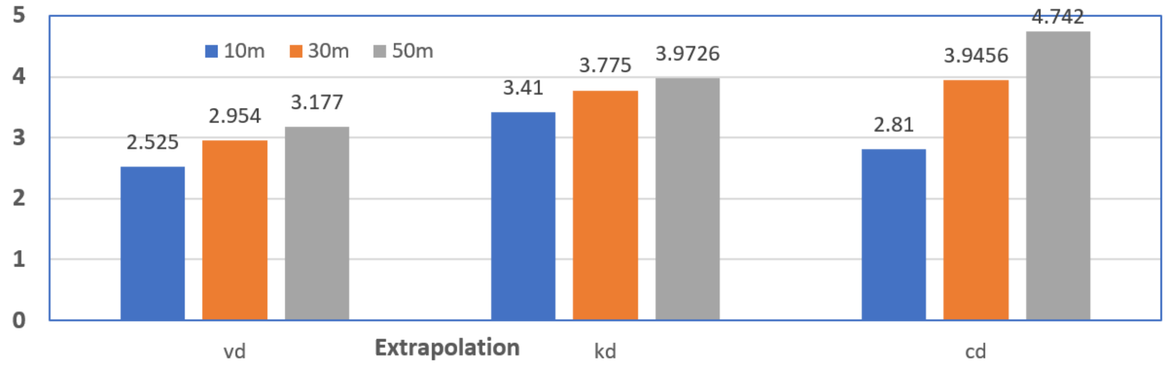

Figure 8. Extrapolating of wind speed, scale parameter and shape parameter, at 30 and 50 m using the annual MWS at 10 m in Sana'a.

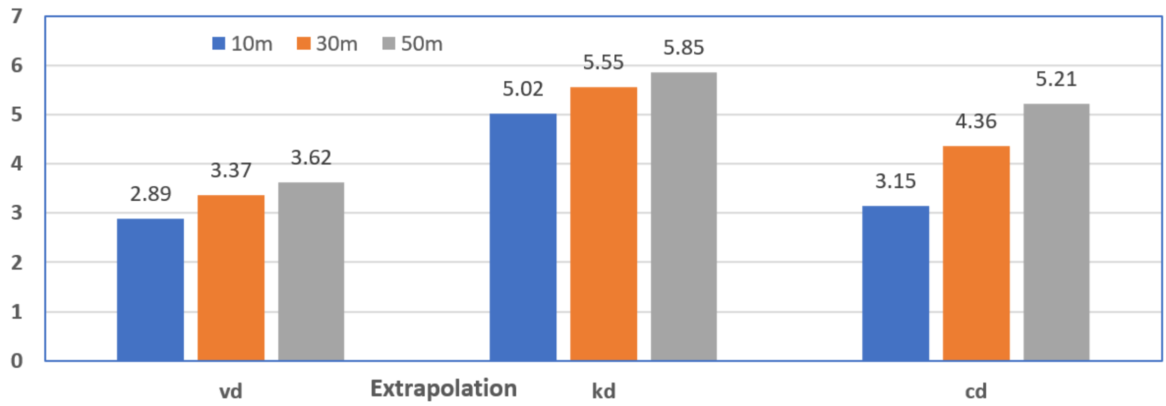

Figure 9. Extrapolating of wind speed, scale parameter and shape parameter, at 30 and 50 m using the annual MWS at 10 m in Amran.

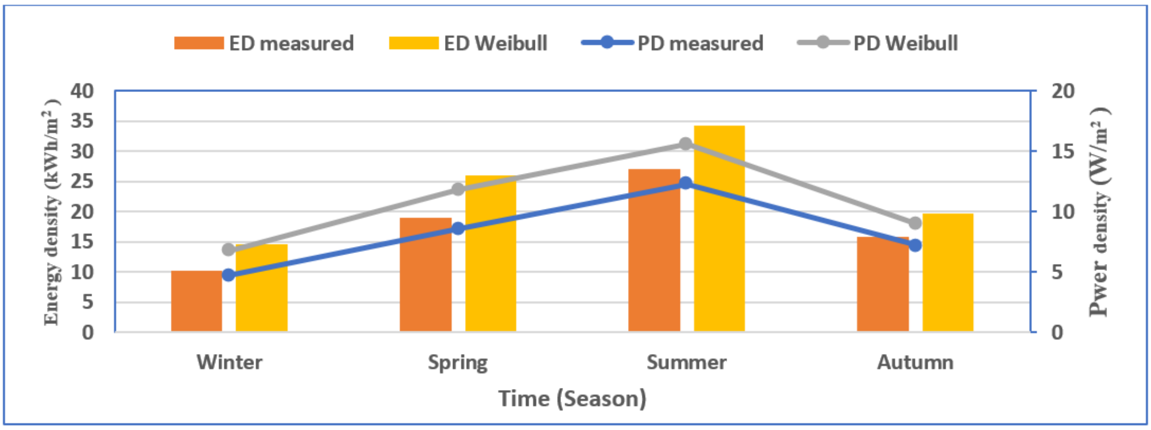

Figure 10. Seasonal WED and WPD for 2010 to 2014 in Sana'a.

higher in the summer.

However, the wind speeds observed at both locations are relatively low compared to the cut-in and nominal speeds required for large-scale wind turbines. Modern utility-scale turbines typically have a cut-in speed of 3–4 m/s and require nominal wind speeds of approximately 10–12 m/s to achieve their rated capacity. The maximum observed wind speeds in Sana'a and Amran are insufficient to support wind energy generation at a megawatt scale using current turbine technology. Interestingly, Sana'a and Amran are very close to the equator with high solar radiation. Based on the findings, solar energy solutions are more appropriate for these locations. Potential applications include solar- powered pumping for agriculture, photovoltaic lighting, and photovoltaic systems for household electrification. Therefore, we recommend that some studies should be conducted to assess the WEP at some sites in Sana'a and Amran governorates outside the cities especially in or near mountainous sites.

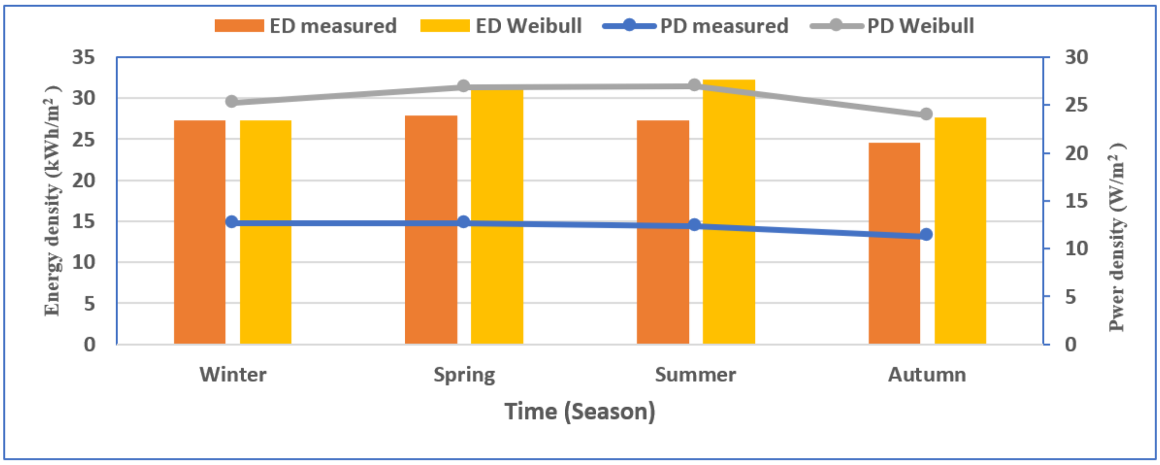

Figure 11. Seasonal WED and WPD for 2010 to 2014 in Amran.

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