Techno-economic assessment and wind energy potential of Nagad in Djibouti

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Article Info

Article history:

Received Jun 12, 2023
Revised Jul 27, 2023
Accepted Aug 2, 2023

Keywords:

Economic analysis
Nagad
Wind power
Wind speed
Wind turbine

ABSTRACT

The use of small scaled horizontal and vertical axis wind turbines in urban installation is increasing over the world. However, in Djibouti, the latter is still in the development phase. The paper presents a techno-economical analysis and wind energy potential for the period of five years (2015-2019) in Nagad based on actual measured wind speed data collected every 10 min at 10 m height. The energy pattern factor method has been used to estimate the Weibull parameters. With this method, the mathematical complexity is reduced with a minimization of the error at any heights and locations when calculating the wind power density. At 50 m height, the shape parameter showed a small variation for different periods. The scale parameter values of 7.78 m/s and 4.8 m/s were obtained in the hot and cold seasons, respectively. The results showed that the Nagad site is suitable for wind power development. According to the economic viability, RX30, Vestas V20, Enercon, Nordex N27, and Vestas V44 wind turbines are recommended for the Nagad site due to their low energy price ranging from 0.05$/kWh to 0.31$/kWh. This is 2-6 times cheaper than the average local tariff of electricity in Djibouti.

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1. INTRODUCTION

The future of the East African population is uncertain due to two major challenges which are the lack of access to modern energy services and the vulnerability associated with climate change. These challenges are at the origin of the reflections engaged to reinvent the energy future by carrying out the necessary transitions towards energy systems that allow responsible growth and reconcile economic development, environmental protection, and the reduction of inequalities.

Access to electricity is a key indicator of a country's level of development. Generation of electricity from renewable energy such as wind, sun (solar thermal and photovoltaic), hydro, and geothermal can play a major role in electricity production in Eastern African countries. Several programs are defined by the Sustainable Energy for All [1], [2] as well as the renewable capacity statistics from the International Renewable Energy Agency [3] to offer a new form of planning centered on needs and to redefine the energy model of the region and the associated policies. Wind energy is the most non-polluting, sustainable and can potentially make a significant contribution to developing countries with poor infrastructure for power generation. The cost, performance, and reliability of renewable energy technologies are significantly improved to the point that they can now compete with conventional energy sources in several applications [4], [5]. Numerous studies have been done to assess the wind speed characteristic and wind power potential in the world [6], [7] and especially in Africa [8]–[10]. According to [11], the levelized cost of electricity and net present cost in Yanbu region of Saudi Arabia are estimated as (0.0885$/kWh and 23.8$) for Enercon E-126 EP4 wind turbine that leads their corresponding values of (0.142$/kWh and38.3$) for WES 30 turbine. Abd in [12] has provided a strategy based on a weather change to find the optimal designing and modelling for four types of wind energy conversion system models using HOMER software. The study has focused on the technical, economic, and profitability calculation for any renewable energy system. In Saswat *et al.* [13], India have demonstrated the effectiveness of the hybrid PV/solar/wind power system, which is given the best and most efficient alternative to conventional energy sources. Idriss *et al.* [14] conducted the potential of wind and solar energy in two rural sites in Djibouti which are Herkalou and Lake Assal. They showed that the studied sites receive the greatest amount of solar radiation compared to other places in the world with the global radiation value of 2,898 kWh/ (m^2. year). In addition to that, the sites have an encouraging potential to develop a hybrid power system for any application. Queen *et al.* [15] have investigated the advantages of integrating natural source of energy from the renewable energies to the prevailing electric power systems. For the two studied standard IEEE system (IEEE 14 bus and IEEE 30 bus), the price of electricity acquired from the grid is lowered by 30% with incorporated renewable energy systems. In addition, Sakhrieh *et al.* [16] provided a techno-economical study of the optimized hybrid system includes photovoltaics, a biogas generator, batteries, and a diesel generator in the rural sites. The levelized cost of energy of 0.06$/kWh and a net present cost of 2,100,000$ have been estimated for the optimized hybrid system. In Egypt, Abdelrahman *et al.* [17] have examined the wind energy potential and the economic feasibility to develop the first wind farm at Elkharga Oasis. With 50 MW wind farm at Elkharga, they concluded that the cost of energy is much cheaper by > 50% than the current tariff in Egypt. Daoudi *et al.* [18] have demonstrated the economic viability of the two onshore wind farms located in the province of Tantan. The results have shown that the two wind farms have a good potential to develop the wind farm with the cost of the production values of 3.45$/kWh and 3.87$/kWh in Tantan-1 and Tantan-2, respectively.

The total potential of wind energy is estimated at 1,300 GW in the Sub-Saharan African regions. The use of micro and small wind turbines in urban and rural installations is increasing over the world, and it is still in the developing phase in East Africa. Djibouti imports all its energy needs while the country has a high potential in renewable energies, untapped until now. Recent surveys conducted as part of the strategy to combat poverty reveals that 49.7% of sedentary households (99.5% of which are in urban area) use electricity to power lighting systems with an average consumption estimated at 228 kWh/year per capita. However, this prominence of energy for Djiboutian households' masks huge disparities in access linked to the availability and high production costs of around 52 DJF/kWh (0.32$/kWh set by Electricité de Djibouti). The country survived until May 2011 on electricity produced from imported petroleum products. Consequently, high production costs are a barrier to access to energy sources for the poorest of the population. In the Republic of Djibouti, a few studies have been conducted to analyze wind power generation [19], more attention should concentrate on the resource of wind speed potential in the urban, peri-urban, and rural areas of the country. During the implementation of the wind project, it is recommended to evaluate the character of the wind speed data, the feasibility depending on the location, the characteristics of wind turbines (horizontal or vertical axis models, cut-in and cut-out velocity, rated velocity, power energy output, and capacity factor), the cost analysis (initial cost, maintenance costs during the lifetime of the turbine), and the energy potential before any wind energy system. Researchers have studied the integration of micro, small, and mid-sized wind systems using several statistical and probability distribution analyses of wind speed data [20]–[22]. According to the International Electrotechnical Commission (IEC:614-00-12), the Weibull 2-parameters are becoming a standard indicator of probability distribution function (PDF) to describe the wind characteristics [23]. Others have investigated by using several numerical methods for fitting the wind speed data as well as the graphical (GM), the moment (MM), and the energy pattern factor (EPFM) methods [24]–[26].

In this work, the wind potential assessment, and the economic feasibility of using commercially available wind turbines are evaluated for the Nagad peri-urban site, located in the southern part of Djibouti-city. Potential Djibouti sites for wind energy generation have not been thoroughly explored as the development of wind project continues to be hampered by the lack of reliable and accurate wind datasets in many parts of Djibouti, as well as the lack of both qualified human resources and accessibility of mountainous and hostile areas of the northern and southern regions for scientists and researchers. Therefore, the objective of this paper is to evaluate the cost of energy production from micro, small and mid-sized wind turbines which will serve as a benchmark in the national energy plan. The statistics and costs provided by this study have enabled government officials and potential investors to propose a strategy to reduce the weight of energy consumption bills in the household budget and to make energy more accessible for all. The fundamental contributions and research originality of this paper can be summarized as:

- Estimating the wind energy, for the first time, in Nagad owing to its windy and less strict topography locations
- Illustrating the performance comparisons of nine wind turbines with various technologies (horizontal and vertical) and characteristics
- Evaluating the economic viability by analysing the cost of energy production

The rest of this paper is subdivided into four sections. Section 2 presents the methodology including the site description and the wind data analysis are presented. In section 3, the results are discussed. Finally, the section 4 presents the conclusion and the recommendation of this study.

2. METHOD

2.1. Study area: Nagad site description and wind data

Nagad is a coastal site (at 11.3124° N and latitude 43.0739° E, altitude 8 m) located near to the International Airport of Djibouti. The site is situated in the south of Djibouti city and is identified as a peri-urban area. Due it's to rather close proximity to the equator, Djibouti is classified as a hot and humid country. This type of climate receives the highest amount of solar radiation compared to other regions. The high level of solar radiation also causes high air temperatures. The meteorological actual wind data were collected and analyzed hourly and every 10 min taken by a mast at 10 m height for a period of five years from 2015 to 2019 using Vantage Pro2 equipment. It includes a mast, an anemometer, a wind vane, a thermometer, and a barometer. The equipment was installed in July 2014 on the roof of the Department of Electrical and Energy in the Faculty of Engineering. Daily average wind speed, wind directions, and temperatures were measured in 10 min time intervals, at 10 m height above the ground level.

Figure 1(a) displays a histogram that illustrates the monthly average temperature (including minimum and maximum). This graph highlights the cold and hot seasons. The period extends from October to April where the climate is rather pleasant, with average temperatures between 18 °C and 34 °C during the day and 17 °C and 32 °C at night. The second season extends from May to September, with very high temperatures. Ranging from 24 °C to 46 °C during the day, and at night it ranges from 20 °C to 42 °C. The difference between the minimum and maximum temperatures in the hot summer months is slightly higher than in the cooler months.

Figure 1(b) shows a monthly average contour map of diurnal mean wind speeds over the studied period. The average wind speeds are higher during the hot period (5-7.5 m/s from 12 p.m. to 8 p.m.) than during the coldest one (4-6 m/s from 12 p.m. to 8 p.m.). The wind characteristics information for a specific site can be combined visually in a wind rose. The latter allows the three essential pieces of information to be grouped in a single graph: wind speed, direction, and frequency by sector.

Figure 1(c) reveals an omnidirectional wind with a dominant wind from the west (5%, 9 m/s) generated by the Ethiopian highlands in summer. This wind which is called "Khamsin" is dry and hot. During the cold season, the city is swept by easterly winds (11.5%, 11 m/s) generated by the trade winds, humid winds from Arabia, and the Gulf of Aden. The annual mean wind speed is 4.28 m/s during the period considered, here 5 years. These representations are the first approach, allowing to have a quick overview of the wind profile of a site for a wind energy application.

Further analyses of wind data were performed in Figure 1(d). The EPFM method is adopted in this study to describe the power density function (PDF) and the cumulative density function (CDF). The EPFM method requires less computation, and easier implementation to calculate the wind power density with less error at any height and location. Based on the latter method, the scale and shape parameters are estimated, which will be discussed in section 3.

2.2. Wind data analysis

2.2.1. Weibull parameters and energy pattern factor method (EPFM)

Several mathematical models have been used to assess the wind speed. In this investigation, the 2-parameters Weibull function is chosen, because it gives a good fit and better measurement of probability distribution function than other statistical methods [27]. The PDF and the CDF of the 2-parameters Weibull can be expressed as:

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

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

where v is the wind speed, c (scale) and k (shape) are the Weibull parameters, respectively.

To calculate k and c values, several methods are proposed in the literature [28], [29]. In this work, the EPFM is selected because it is a valuable and direct method that does not demand repetitions, simple and easy to tool and formulate. E_{pf} is defined the as ratio between the mean of cubic wind speed ($\overline{v^3}$) to the cube of mean wind speed ($\overline{v}^3$). The E_{pf} can be calculated as (3) [21].

$$E_{pf} = \frac{\overline{v^3}}{\overline{v}^3} = \frac{\frac{1}{n}\sum_{i=1}^{n} v_i^3}{\left(\frac{1}{n}\sum_{i=1}^{n} v_i\right)^3} \tag{3}$$

Then, the values of k and c are determined by (4) and (5).

$$k = 1 + \frac{3.69}{(E_{pf})^2} \tag{4}$$

$$c = \frac{\overline{v}}{\Gamma\left(1+\frac{1}{k}\right)} \tag{5}$$

With *Γ(.)* is the gamma function.

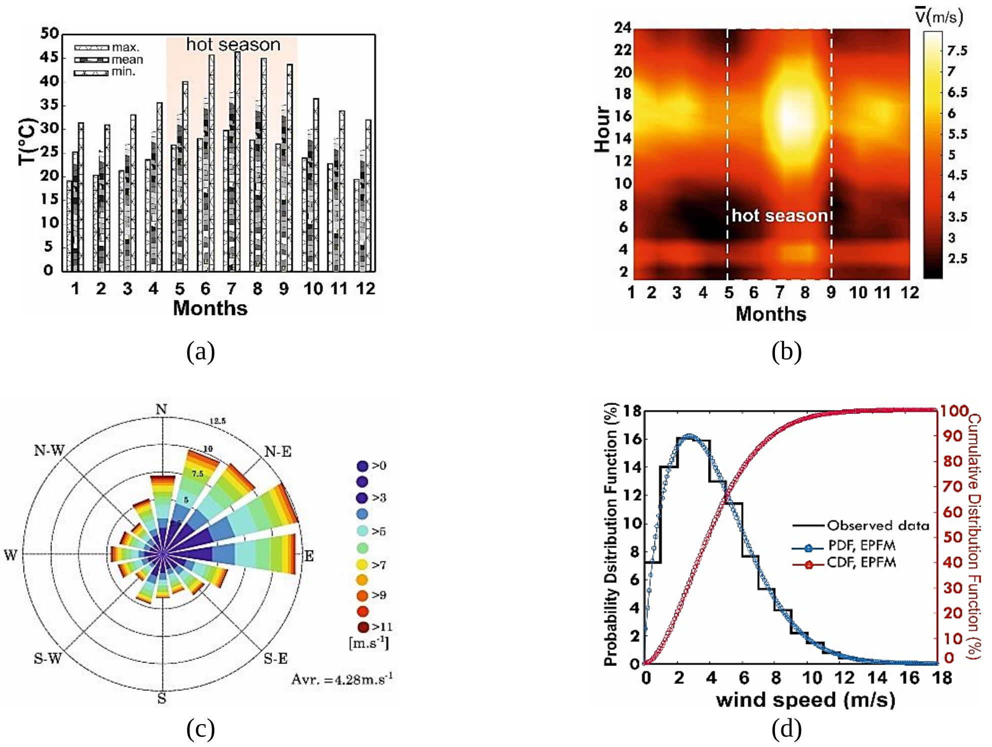

Figure 1. Nagad site wind data covering 2015-2019 (a) monthly mean temperature of Nagad's wind speed data, (b) monthly (and daily diurnal) contour map of the hourly mean wind speed data, (c) wind rose diagram, and (d) PDF and CDF curves compared to the observed wind data

2.2.2. Wind speed extrapolation with height

The wind speed increases with heights, the power law is used for its simplicity in this study to extrapolate wind speed at different altitudes [30]. The wind speed variation with height can be mathematically expressed as (6).

$$v(h) = v_0 \left(\frac{h}{h_0}\right)^{\alpha} \tag{6}$$

Where v_0 is the wind speed at the initial height h_0 and α is the power-law commonly admitted to be 1/7. As the wind speed varies with height, similarly, the Weibull parameters c and k are also functioning of hub height. Using (7) and (8), the parameters can be calculated.

$$c(h) = c_0 \times \left(\frac{h}{h_0}\right)^n \tag{7}$$

$$k(h) = k_0 \times \frac{\left(1-0.088ln\left(\frac{h}{h_0}\right)\right)}{\left(1-0.088\,ln\left(\frac{h}{10}\right)\right)} \tag{8}$$

Where c_0 and k_0 are Weibull parameters at h_0. The exponent n is given by (9).

$$n = \frac{\left(0.37-0.088ln(c_0)\right)}{\left(1-0.088\,ln\left(\frac{h}{10}\right)\right)} \tag{9}$$

2.2.3. Evaluation of wind power density, energy density, capacity factor, power, and accumulated annual energy of the wind turbines

The wind power is mathematically expressed as (10) [31].

$$P(v) = \frac{1}{2}\rho A\,\overline{v}^3(\mathrm{W}) \tag{10}$$

The air density ρ is assumed to be 1.225 kg/m^3 and the rotor area of the turbine is A (m^2). The wind power density (WPD) in a selected site at a period with Weibull parameters can be expressed as (11).

$$WPD = \frac{P\,(v)}{A} = \frac{1}{2}\rho\, c^3\Gamma\,\left(1+\frac{3}{k}\right) \quad (W/m^2) \tag{11}$$

While wind energy density (WED) is defined as the power density over a period, energy density can be evaluated using (12). Where T is a period of time (hour).

$$WED = WPD \times T \quad (Wh/m^2) \tag{12}$$

To evaluate the efficient and best-suited wind turbine for the Nagad site, nine commercial turbines of the site were selected. Average power output ($P_{e.ave}$), capacity factor (CF), and accumulated annual energy (AEP) are the important performance parameters to study wind speed installed in a given site. The $P_{e.ave}$ and CF of a wind turbine are calculated by (13) and (14).

$$P_{e.ave} = P_{eR}\left(\frac{e^{-\left(\frac{v_c}{c}\right)^k}-e^{-\left(\frac{v_r}{c}\right)^k}}{\left(\frac{v_r}{c}\right)^k-\left(\frac{v_c}{c}\right)^k} - e^{-\left(\frac{v_f}{c}\right)^k}\right) \tag{13}$$

$$CF = P_{e.ave}/P_{eR} \tag{14}$$

Where v_c, v_r and v_f are the cut-in, rated, and cut-off wind speeds respectively. P_{eR} is the rated electrical power of the wind turbine. The AEP is calculated over a period by using (15) [32]. Where t is the time, example for one a year period it has 8760 in hours.

$$AEP = CF \times P_{eR} \times t \quad (kWh) \tag{15}$$

2.2.4. Wind energy cost analysis

In a given site, to assess the feasibility of the wind farm, the cost of energy is the most important parameter to evaluate the economic viability. For evaluating wind energy cost, several methods have been discussed in [33]. However, the present value of costs (PVC) method is commonly used, and it is adopted in this study. The PVC is given as (16).

$$PVC = I + C_{omr}\left[\frac{1+i}{r-i}\right] \times \left[1-\left(\frac{1+i}{1+r}\right)^{lt}\right] - S\left(\frac{1+i}{1+r}\right)^{lt} (\$) \tag{16}$$

The cost of produced energy (in kWh) by turbines at the respective location was estimated as 20% for the investment cost (*I*), the inflation (i) and interest (r) rates are 2% and 11.2% [34], with the lifetime (lt) of wind turbines is 20 years. The operation, maintenance, and repair cost (Comr) are 15% (minimum cost) and 25 % (maximum cost). The scrap value (S) is 10 %. The cost per kWh of electricity generated (UCE) can be determined by (17) [33].

$$UCE = \frac{PVC}{AEP} \quad \left(\frac{\$}{kWh}\right) \tag{17}$$

3. RESULTS AND DISCUSSION

3.1. Wind speed analysis: analysis of Weibull parameters, power, and energy densities

To evaluate the availability of wind power at a site, the plot of the probability density function (PDF) curve is essential. The annual average k and c Weibull parameters are calculated using the probability distribution for the considerate wind speeds, which are then plotted with the cumulative density function curve see Figure 1(d). The most probable wind speed occurs at a speed of 2.5 m/s with a probability of 16.2%, while wind speed greater than 10 m/s shows a very low probability. Table 1 presents the monthly, seasonal, and yearly average of wind speed, the Weibull parameters (c and k), and the power and energy densities (WPD and WED) for the studied site at 10 m height.

The results show that the whole year is divided into two seasons: cold (from October to April) and hot (from May to September) seasons. The highest mean wind speeds were observed in July and August with values of 4.99 m/s and 5.30 m/s, respectively. The lowest was obtained in April with a value of 3.38 m/s.

The EPFM value of parameter k ranges from 1.71 in April to 1.99 in August while parameter c varies between 3.38 m/s in April to 5.30 m/s in August. The higher values of c are observed during the hot season (5.08 m/s) and lower during the cold season (4.59 m/s). The mean seasonal values of k parameter are observed to be 1.72 and 1.65 corresponding to the cold and hot seasons, respectively. In addition, the lower values of wind power densities and energies are obtained as 68.32 W/m² and 49.19 kWh/m² respectively in April while the higher values of 222.56 W/m² and 164.84 kWh/m² are computed in July, respectively. Also, the yearly mean power and energy densities are 111.49 W/m² and 976.65 kWh/m²/year, respectively.

Table 1. Mean wind speed, Weibull parameters, WPD and WED over the considered period

Period	$\overline{v}$ (m/s)	k (-)	c (m/s)	WPD (W/m²)	WED (kWh/m²)
Jan	4.7	1.91	5.6	125.52	93.39
Feb	3.99	1.83	4.82	93.87	63.08
Mar	3.89	1.82	4.58	92.73	68.99
Apr	3.38	1.71	4.33	68.32	49.19
May	3.39	1.72	4.13	68.53	50.99
Jun	3.89	1.83	4.59	94.05	67.71
Jul	4.9	1.98	5.42	222.56	164.84
Aug	5.30	1.99	6.11	222.06	165.21
Sep	3.39	1.72	4.33	68.53	49.34
Oct	3.99	1.83	4.82	94.09	70.00
Nov	3.89	1.83	4.59	93.78	67.52
Dec	3.99	1.83	4.82	93.94	69.89
Cold season	4.10	1.72	4.59	94.88	482.78
Hot season	4.54	1.65	5.08	136.10	499.78
Annual	4.05	1.83	4.84	111.49	976.65

3.2. Monthly mean wind speed and WPD at 10 m and 50 m

The WPD classification is commonly used [35] and is established for classifying the wind potential. The wind power resource can be divided into 7 categories from poor (class=1) to excellent (class=5, 6, and 7) [7], [36]. According to Table 2 and as shown in Figure 2(a), for the July and August, Nagad site shows good wind energy with WPD values higher than 600 W/m² ($\overline{v}$ =7.2 m/s) at 50 m height. The mean WPD is higher than 350 W/m² in January while for the other months it ranges from 200 to 300 W/m² (with $\overline{v}$ varies from 4.5 to 5.3 m/s).

In Figure 2(b) the annual wind energy density was recorded at 339 W/m² (moderate, class 3 with $\overline{v}$ =5.4 m/s) while it was measured at 297 W/m² (marginal, class 2 with $\overline{v}$ =5.2 m/s) in the cold season and 400 W/m² (moderate, class 3 with $\overline{v}$ =5.7 m/s) in the hot season. From the above classification, the Nagad site has reasonable wind energy resources and is suitable for harnessing wind turbines applications.

Table 2. Classification of WPD [35], [36]

Wind class	At 10 m height		At 50 m height		Wind class	At 10 m height		At 50 m height	
	$\overline{v}$ (m/s)	WPD (W/m²)	$\overline{v}$ (m/s)	WPD (W/m²)		$\overline{v}$ (m/s)	WPD (W/m²)	$\overline{v}$ (m/s)	WPD (W/m²)
1	<4.4	<100	<5.6	<200	5	6.0-6.4	250-300	7.5-8.0	500-600
2	4.4-5.1	100-150	5.6-6.4	200-300	6	6.4-7.0	300-400	8.0-8.8	600-800
3	5.1-5.6	150-200	6.4-7.0	300-400	7	>7.0	>400	>8.8	>800
4	5.6-6.0	200-250	7.0-7.5	400-500					

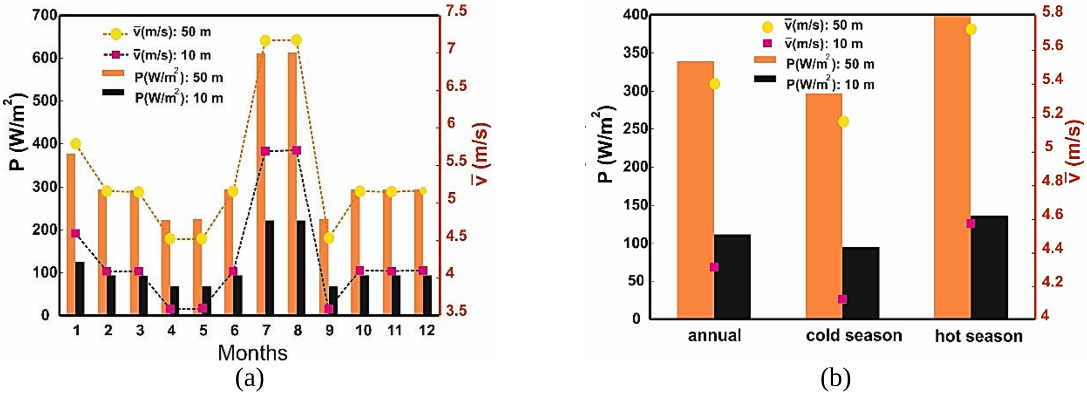

Figure 2. Extrapolation for (a) monthly and (b) annual and seasonal results of mean wind speed and power density at selected heights

3.3. Performance of nine small wind turbines: monthly, yearly and seasonal analysis

In this part of the study, the performances of the nine different wind turbines were calculated. These turbines are selected based on their availability in the Republic of Djibouti and for their tower heights. The characteristics of the wind turbines are given in Table 3. Here, HAWT and VAWT mean the type of Horizontal and Vertical Axis Wind Turbines, respectively. Seven HAWTs namely Aeolos, Antaris, RX30, Vestas V20, Enercon, Nordex, and Vestas V44, and two VAWTs namely Turby and Sun surf were used to estimate the energy production for all the considered years and were analyzed.

Table 3. Characteristics of selected commercial wind turbines

Type	Turbine model	Vc (m/s)	Vr (m/s)	Vf (m/s)	Rotor diameter (m)	Hub height (m)	PeR (kW)
HAWT	Antaris	2.8	13	25	4	12	3.50
	Aeolos	3.5	12	25	8	18	10
	RX30	3	10	25	16	18	30
	Vestas V20	5	17.50	25	20	24	100
	Enercon	3	12	25	16.20	30	55
	Nordex N27	3	13	25	27	30	150
	Vestas V44	5	17	20	44	50	600
VAWT	Turby	3.5	12	14	2	15	2.5
	Sun surf	1.8	8	25	9	18	10

The annual and seasonal mean variation of $\bar{v}$, k, and c are shown at different hub heights corresponding to the wind turbines heights 12 m, 15 m, 18 m, 24 m, 30 m, and 50 m. At 50 m, the mean wind speed value is 5.37 m/s, k and c values are 1.96 and 7.41 m/s, respectively. The shape parameter shows a small variation for different heights and periods, whereas the scale parameter values vary between 5.30 m/s (at 12 m height) to 7.78 m/s at 50 m in the hot season. For the cold season, the c parameter variation ranges from 4.8 m/s (at 12 m height) to 7.15 m/s at 50 m, which is a sign that the site is suitable for wind applications. For all heights, it is noted that the hot season presents high wind characteristics than the cold season.

Thus, $P_{e,ave}$, *CF*, and *AEP* given by these wind turbines are calculated using (13), (14), and (15). Additionally, Figure 3 shows the monthly variation of estimated *CF* and *AEP* of wind turbines. For the monthly analysis, the outcomes can be listed as:

- The mean capacity factors and annual energy output values were recorded in August, as 28.97% and 215 kWh for Aeolos small-scale wind turbine, whereas the minimum values were 22.80% and 59.3 kWh for Antaris turbine, given in Figure 3(a). In this case, depending on the hub height of the wind turbine and P_{eR} of the turbine, the Aeolos turbine produces maximum energy compared to Antaris.
- Figure 3(b) depicts the mean CF and AEP for the VAWT turbines. The maximum mean CF value is obtained as 50.86% in August and a minimum value of 27.29% in April for the Sun surf turbine. The maximum mean AEP value is obtained as 378.4 kWh in August while the minimum value is computed as 196.6 kWh in April. The result shows that the Sun surf turbine generates more energy than the Turby wind turbine.
- For the Enercon turbine, the mean AEP was maximum for August with 1515 kWh and least for April with 713 kWh as described in the Figure 3(c). The highest mean CF occurs in August with a value of 37.03% and the lowest mean CF occurs in April with a value of 17.99%. On observing the RX30 turbine, it can be

observed that the maximum AEP available in August was 899.2 kWh (with CF=40.28%) and the minimum mean AEP value of 402.8 kWh (with CF=18.64%) was present in April.

- The mean CF and AEP generated by different mid-sized wind turbines namely Nordex, Vestas V20, and Vestas V44 at three hub heights are estimated and shown in Figure 3(d). In August, the highest capacity factor was 32.33% for the Nordex turbine followed by 21.22% for Vestas V44 and 13.20% for Vestas V20. Also, for the same month, the minimum AEP values of about 3.60 MWh, 9.82 MWh, and 9.47 MWh are observed for the Nordex, Vestas V20, and Vestas V44 respectively.

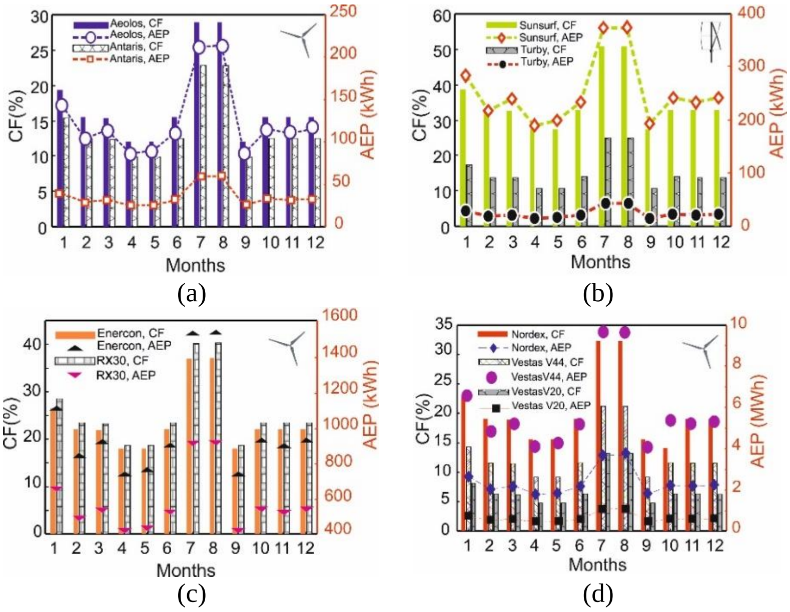

Figure 3. Monthly variation of CF and AEP for (a) Aeolos and Antaris, (b) Sun surf and Turby, (c) Enercon and RX30, and (d) Nordex, Vestas V44, and Vestas V20

3.4. Cost of energy production: comparison and analysis

Table 4 shows the annual and seasonal computed values of PVC ($) and the UCE ($/kWh) while the corresponding cost of Comr are 15% and 25% of the total investment. The results show that the maximum PVC ranged from 18136.79$ to 47953.69$ for RX30 and Vestas V44 wind turbines. The Antaris turbine produces the highest annual cost of 2.31$/kWh and the Vestas V44 generates the lowest annual cost of 0.034$/kWh, followed by Nordex N27 with a cost of 0.060$/kWh. As indicated in Table 4, the highest cost of electricity in the cold season was 6.28$/kWh for the Antaris wind turbine, and the lowest was 0.09$/kWh for the Vestas V44. Hence, with regards to the hot season, the highest value of UCE was 3.42$/kWh for Antaris, and the lowest value of UCE was 0.05$/kWh for Vestas V44.

Table 4. Results of PVC (in $) and UCE (in $/kWh) for each turbine
(min. and max. represent 15% and 25% of the total investment)

Type	Turbine model	PVC($)		Annual UCE ($/kWh)		Cold season UCE ($/kWh)		Hot season UCE ($/kWh)	
		Min.	Max.	Min.	Max.	Min.	Max..	Min.	Max.
HAWT	Antaris	19691.89	20447.24	2.22	2.31	6.05	6.28	3.30	3.42
	Aeolos	20849.23	21648.97	0.67	0.69	1.81	1.88	0.99	1.03
	RX30	17466.80	18136.79	0.12	0.13	0.33	0.35	0.19	0.20
	Vestas V20	28653.04	29752.12	0.21	0.22	0.61	0.63	0.30	0.31
	Enercon	19481.20	20228.55	0.081	0.085	0.21	0.22	0.12	0.13
	Nordex N27	32780.19	34037.58	0.058	0.060	0.15	0.16	0.08	0.09
	Vestas V44	46182.22	47953.69	0.033	0.034	0.08	0.09	0.04	0.05
VAWT	Turby	16302.32	16927.65	2.35	2.44	6.34	6.58	3.54	3.68
	Sun surf	37179.34	38605.47	0.59	0.62	1.53	1.58	0.93	0.97

The local average electricity cost value is 0.32$/kWh in Djibouti. Comparing the estimated tariffs obtained by the RX30, Vestas V20, Enercon, Nordex N27, and Vestas V44 wind turbines with the local cost price of electricity (0.32$/kWh), indicate that the estimated tariffs are lower than the local cost price of electricity. The latter remark is highlighted in bold in Table 4. Their cost reveals that the horizontal wind turbines are viable renewable energy sources to serve local communities and to intensify the production of electricity in the Nagad site.

4. CONCLUSION AND RECOMMENDATIONS

The performance comparisons and techno-economic analysis of HAWT and VAWT wind turbines in a hot climate have been studied at Nagad peri-urban site in Djibouti city. The wind data covering 2015-2019, recorded every 10 min, were analyzed for the wind speed characteristics and economic feasibility of wind systems. The results show that the average wind speeds are higher during the hot period (5-7.5 m/s from 12 p.m. to 8 p.m.) than the coldest one (4-6 m/s from 12 p.m. to 8 p.m.) at 10 m hub height. The annual mean wind speed over the considered period was 4.05 m/s. The performance of the selected empirical EPFM method was observed and was close to the measured wind speed data of Nagad k values ranges from 1.65 to 1.99 while c values vary between 4.13 m/s to 6.11 m/s at 10 m. At 50 m, the annual mean wind speed was 5.37 m/s, k was 1.96 and c was 7.41 m/s. For the cold season, c was 7.15 m/s, which is a sign that the Nagad site is suitable for wind power technologies development. At 50 m hub height, the annual WED was recorded at 339 W/m² while it was measured at 297 W/m² in the cold season and 400 W/m² in the hot season. It is important to note that Nagad site was classified as class 3 and was considered suitable to harness wind power. In August, the highest CF was 32.33% for the Nordex turbine followed by 21.22% for Vestas V44 and 13.20 % for Vestas V20. The minimum AEP values of about 3.60 MWh, 9.82 MWh, and 9.47 MWh are observed for the Nordex, Vestas V20, and Vestas V44, respectively.

The economic analysis showed that RX30, Vestas V20, Enercon, Nordex N27, Vestas V44 wind turbines are recommended for Nagad due to a low price of energy between 0.05$/kWh and 0.31$/kWh. For Vestas V44, Nordex N27, and Enercon, the price of energy is 2-6 times cheaper than the average local tariff of electricity. The vertical turbines are not recommended for the Nagad site.

ACKNOWLEDGEMENT

The authors of this article wish to acknowledge the financial support from the University of Djibouti and the contributions of Eng. Omar Abdoulkader Mohamed (INSTAD).

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