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Wind and solar energy potential in Herkalou and Lake Assal locations, Djibouti

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ABSTRACT

The absence of meteorological data to identify the energy resources and the available energy potential represented a major obstacle in some areas in Djibouti. To solve this data problem, in this paper, wind and solar potential were assessed by collecting daily and monthly wind and solar data for the period from 1 January to 31 December 2020, for Herkalou and Lake Assal site. This study highlights that the wind resources in the Lake Assal location are falling into class 7 with high wind speed value of 16 $m.s^{-1}$ and the wind energy reaching1700 kWh/m^2 at 100 m height above ground level. While the Herkalou site shows a lower potential with value of 7.5 $m.s^{-1}$ and 160 kWh/m^2. The solar potential shows a similar distribution and a constantly high level of solar radiation throughout the year, with the monthly maximum global radiation peaks of around 900 W/m² between 11.00 and 14.00 pm for both sites. The highest monthly average of global solar irradiation values was 5.29 kWh/m^2 day^{-1} and 6.90 kWh/m^2 day^{-1} in March for Herkalou and Lake Assal, respectively. Results obtained in this study are favorable to deploying the solar and wind technologies for the studied sites.

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1. INTRODUCTION

Africa is a vast continent. The level of development of the economic and energy sectors varies greatly between the 54 African countries. The situation of electrification is still low in Africa. One inhabitant in two does not have access to electricity, and that is to say approximately 650 million people. The north is almost 100 % equipped, but it is quite different from the sub-Saharan part of the continent with, significant disparity.

To fight against these energy deserts, renewable energies have imposed themselves in recent years. A better understanding and mapping of available resources is needed to enable governments to set ambitious but realistic targets and implement effective supportive policies, in order to successfully exploit these abundant resources. East Africa has potential for renewable energies, it is enough to undergo the exploitation of geothermal energy along the Rift Valley in East Africa or wind and solar energy in the Horn of Africa and along with several coastal areas. Despite the high wind and solar energy potential in some east African countries, wind and solar electricity generation are still very limited. Therefore, the investing commitment in wind and solar energy resources are crucial. The available wind measurements in some studies reveal that Djibouti, the case study, has a potential for electric power generation using wind and solar technologies [1]–[3].

Djibouti has a limited, costly, and inefficient network of power systems, forcing the country to import the majority of its electricity from the hydropower plants in Ethiopia. The alternative is to achieve 100% renewable energy production in order to limit its total dependence on imports within the framework of the government program. Consequently, the examination of wind and solar data resources over the country can improve the opportunities and overcome the challenges to develop wind and solar power generation.

A number of scientific papers have been published in wind potential evaluation [4]–[8]. Depending on the location, it is decisive to investigate the technical wind energy potential, to describe the Weibull characteristics of the wind, and its corresponding rose diagram, as well as the major wind flow contributing to the resource, and the velocity probability distribution. Current research is conducted for estimating the wind potential using various methods for estimating Weibull parameters [5]–[8]. The potential of wind energy was investigated in the Tigray region of Ethiopia [9]. Saad *et al.* [10] presented uncertainty studies using Monte Carlo-Beta probability density function to model continuous random variable of solar radiation under tropical climate. Genetic Programming Techniques [11] and artificial neural network [12] methods are also used as weather prediction models. Salah *et al.* [13] investigated wind energy potential for different regions and seasons in Saudia Arabia. Nefabas *et al.* [14] performed wind power production using ERA5 reanalysis data and for Ashegoda wind farms, they demonstrate a good correlation between the measured and simulation model result. Michael *et al.* [15] conducted the potential of wind energy resources and determined suitable wind turbines in the coastline region of Dar es Salaam, Tanzania. Mohamed [16] analyzed the generation capacity of wind energy in Egypt, Elkharga Oasis. In addition, the study analyzed the economic potential. They concluded that the Elkharga site has enormous potential because, at 120 m altitudes, the wind velocity reaches 8.63 m/s, moreover the proposal's energy cost is 50% more affordable than the local. Wabukala *et al.* [17] conducted a review to assess the wind energy opportunities and challenges in Ouganda. Idriss *et al.* [18] performed wind data analysis in Djibouti-city and their results reveal that the wind is classified under Class 1 with the mean wind speed value of 1.2 m/s (3 W/m^2). As well as wind energy, solar energy is the most abundant in the world [11], [19].

Therefore, the aim of this paper is to analyze wind and solar data resources at the two different locations in the middle and north regions of Djibouti namely Lake Assal and Herkalou. Despite the importance of these sites, due to the economic and ecological services they provide, there is a lack of work on the measured wind and solar radiation data. Satellite data is often used to fill this gap and map climate parameter distributions in the country. This is why, for the first time, in this paper, the investigation for the two sites is assessed to determine the available wind and solar resources potential based only on wind speed and solar radiation measured data.

2. METHOD

For this study, the National Meteorological Agency of Djibouti installed two meteorological stations. Equipped with sensors (pyrgeometer, wind speed and direction sensors, pyranometers with a range of 0-2000 W/m^2, temperature, relative humidity, and atmospheric pressure sensors) to record every 10 min interval wind speed and solar irradiation measurements at 10 m and 20 m height in altitude for Herkalou as well as for Lake Assal locations. Herkalou is a hill and the site is located at latitude 12°27'14" North, longitude 43°17'24" East in Obock. The Lake Assal is located at 153 m below sea level at latitude 11°39'52" North, longitude 43°17'24.87" East. These stations were acquired and calibrated from NRG Systems. The collected data at 10 m and 20 m height used to describe the wind potential in Herkalou and Lake Assal refer to a one-year measurement from 1 January to 31 December 2020. Despite the violent wind of the Lake Assal site, the quality of the recording data was good during the studied period. Figure 1 presents the flowchart of the proposed methodology. This process gives the available resources information on the solar and wind power potential for the studied sites.

2.1. Weibull (PDF) and cumulative (CDF) distribution function

The wind data distribution is an essential step in the estimation of the energy potential of the wind. In order to easily determine the technical and economic characteristics, several mathematical functions exist in the literature [20], [21]. The Weibull probability distribution function in wind power studies is highly taken into account [22], [23]. The PDF and CDF are expressed below as follows:

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

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

With
V: Wind speed; c: scale parameter;
k: Shape parameter.

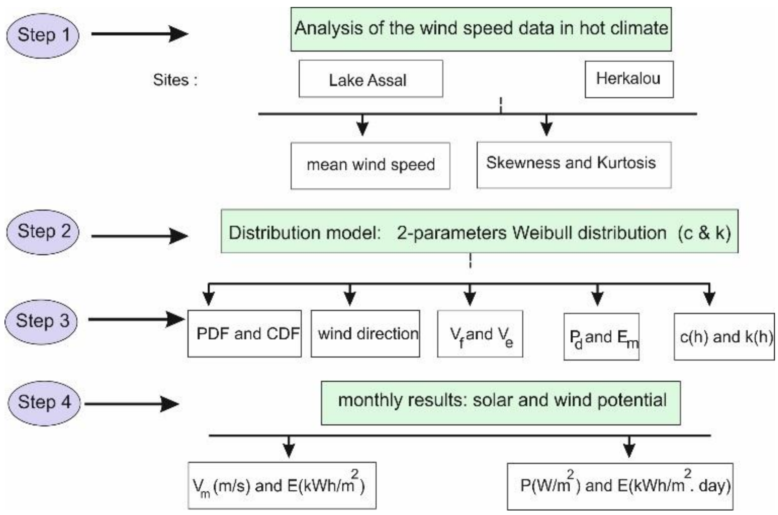


Figure 1. Flow chart of the proposed methodology

After determining the scale in addition to the shape parameters from the Weibull distribution function and estimating the wind energy potential, two significant wind speeds are determined which are the most probable wind speed (V_f) and the wind speed carrying maximum energy (V_e). These equations are expressed as (3) and (4) [24], [25].

$$V_f = c\left[\left(\frac{k-1}{k}\right)\right]^{1/k} \quad (3)$$

$$V_e = c\left[\left(\frac{k+2}{k}\right)\right]^{1/k} \quad (4)$$

2.2. Power density (P_d) and energy density (E_m)

The most common method for determining the wind resource available in the selected side is by computing the power density P_d. The measured mean P_d is calculated as (5).

$$P_d = 0.5\rho {V_m}^3 \quad (5)$$

Where ρ =air density (referred as 1.225 kg/m^3[7]); V_m is the measured average wind speed (m.s-1).
Furthermore, the energy density (E_m) for the studied site can be expressed as (6) [26].

$$E_m = P_d \times T \quad (6)$$

Where T is the time 720 H and 8760 H were taken for the monthly and annual duration, respectively.

2.3. Wind parameters extrapolation

To compute the wind speed at the specified height, there are some mathematical models. One of them is the logarithmic law expressed as (7) [27], [28].

$$V_2 = V_1\left[\frac{ln\left(\frac{Z_2}{Z_0}\right)}{ln\left(\frac{Z_1}{Z_0}\right)}\right] \quad (7)$$

Where V_2 is the wind speed (m/s), calculated at the desired height (depending on V_1 measured at the initial height); and Z_0 is the aerodynamic factor of the site roughness and is equal to 0.0024.

The wind speed varies with the hub height, similarly, the shape and scale parameters are also varying according to the height. Using the [29], [30] the parameters can be calculated using:

$$c(h) = c_0 \times \left(\frac{h}{h_0}\right)^n \quad (8)$$

$$k(h) = k_0 \times \frac{\left[1-0.088ln\left(\frac{h}{h_0}\right)\right]}{\left[1-0.088\,ln\left(\frac{h}{10}\right)\right]} \quad (9)$$

where c_0 and k_0 are Weibull parameters at a reference height h_0. The exponent, *n*, can be calculated by the (10).

$$n = \frac{[0.37-0.088ln(c_0)]}{\left[1-0.088ln\left(\frac{h}{10}\right)\right]} \quad (10)$$

2.4. Statistical indicators

Two statistical indicators which are skewness and kurtosis are calculated to investigate the distribution pattern of wind data [31]:

$$Skew = \frac{1}{n-1}\sum_{i=1}^{n}\frac{(V_i-V_m)^3}{\sigma^3} \quad (11)$$

where, σ is the standard deviation; V_i is the i^{th} wind speed value in the dataset; while *n* is the dimension of the wind data.

3. RESULTS AND DISCUSSION

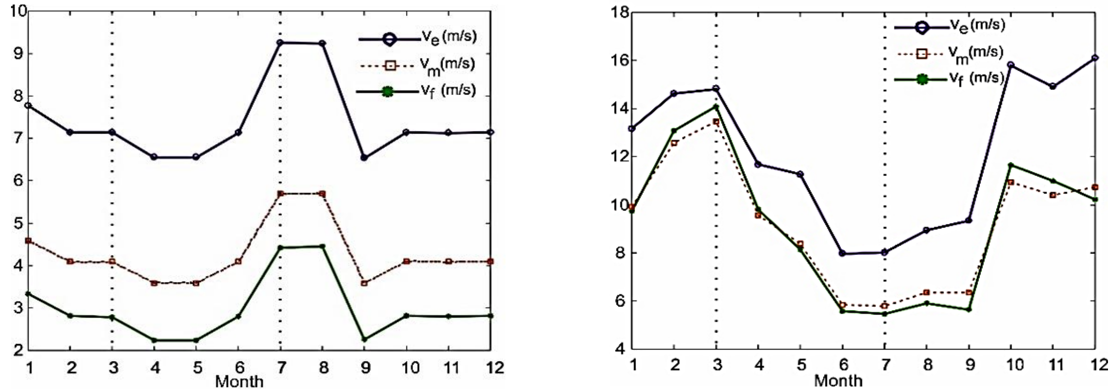
Table 1 lists the measured wind speed and Weibull parameters for the studied locations. For Herkalou site, the mean wind speed ranges from 3.59 $m.s^{-1}$ in May to 5.7 $m.s^{-1}$ in August, at 10 m height in altitude. The mean variation of the V_f wind speed is lower compared to the V_e wind speed for both sites. In addition, for Herkalou site, the mean wind speed is significantly increased throughout the hot time of the year in contrast to the cold one. The Weibull parameters c and k are also shown in Table 1. At 10 m height in altitude, for Herkalou, the scale values vary between 4.01 and 6.43 $m.s^{-1}$ while the k values vary between 1.63 and 1.95. For the Lake Assal site, the c parameter values are higher with a maximum value of 14.36 $m.s^{-1}$ (in March) and a minimum value of 6.5 $m.s^{-1}$ (in July) while the k parameter values range between 2.34 (September) and 7.46 (March).

Table 1. Monthly average of wind speed and Weibull parameters for Herkalou and Lake Assal

	Herkalou (10 m)					Lake Assal (20 m)				
	V_m ($m.s^{-1}$)	c ($m.s^{-1}$)	k (-)	V_e ($m.s^{-1}$)	V_f ($m.s^{-1}$)	V_m ($m.s^{-1}$)	c ($m.s^{-1}$)	k (-)	V_e ($m.s^{-1}$)	V_f ($m.s^{-1}$)
Jan.	4.59	5.17	1.82	7.76	3.33	9.94	11.13	3.02	13.16	9.74
Feb.	4.09	4.6	1.74	7.14	2.81	12.57	13.68	5.03	14.62	13.09
Mar.	4.09	4.58	1.73	7.14	2.78	13.48	14.36	7.46	14.82	14.08
Apr.	3.59	4.01	1.63	6.55	2.23	9.57	10.51	4	11.67	9.81
May	3.59	4.01	1.63	6.55	2.23	8.39	9.41	2.91	11.26	8.14
Jun.	4.09	4.59	1.74	7.12	2.80	5.84	6.56	2.78	7.97	5.58
Jul.	5.69	6.42	1.94	9.25	4.41	5.78	6.5	2.67	8.01	5.45
Aug.	5.7	6.43	1.95	9.23	4.44	6.36	7.16	2.58	8.94	5.92
Sept.	3.59	4.02	1.64	6.53	2.26	6.36	7.17	2.34	9.33	5.65
Oct.	4.1	4.6	1.74	7.14	2.81	10.95	13.33	3	15.80	11.64
Nov.	4.09	4.59	1.74	7.12	2.80	10.42	12.58	3	14.91	10.98
Dec.	4.1	4.6	1.74	7.14	2.81	10.72	12.64	2.46	16.09	10.22

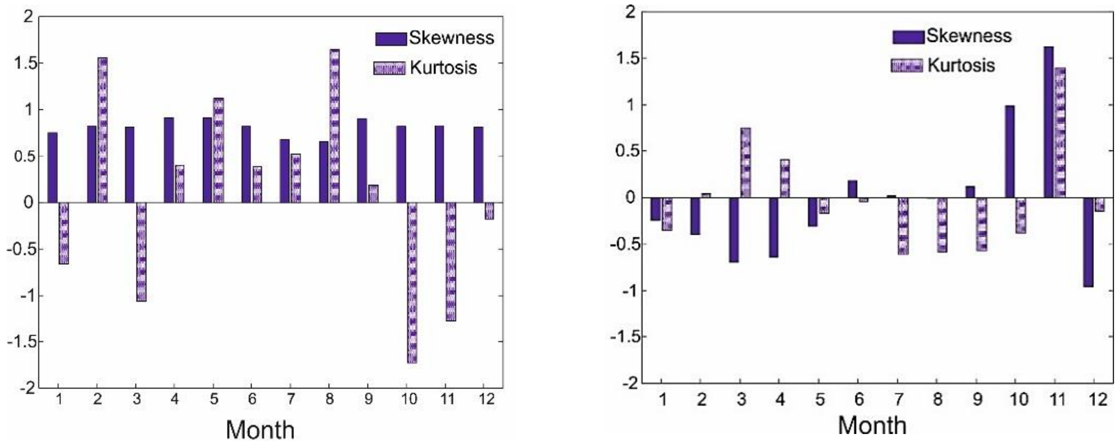
However, in Figure 2, it can be clearly seen that the cold season between October and April is windy for the Lake-Assal site at 20 m in altitude elevation according to the ground level. The average wind speed varies between 5.78 $m.s^{-1}$ and 13.48 $m.s^{-1}$. At the greater height, the difference between V_m and V_f wind speed is small independently from the season.

Figure 3 shows a histogram of monthly skewness and kurtosis of the wind speed values for the Herkalou and Lake Assal sites. These statistical analyses are to characterize the variability of a wind data set and the studied site. In Figure 3(a), the skewness for Herkalou is positive and below 1 during the studied period. The latter indicates the stability of the wind's dataset. The kurtosis values are negative for January, March, October, November, and December which indicate a flatter distribution. For the Lake-Assal site in Figure 3(b), kurtosis values are very low (below -1), hence, a light tail is seen. Skewness values are negative between January and May which mean that the wind distribution is fatter than the tail on the right side where a near-zero means a good symmetric data such a normal distribution.



(a) (b)

Figure 2. Monthly mean variations of measured V_m, V_f and V_e for (a) Herkalou (10 m) and (b) Lake Assal (20 m)



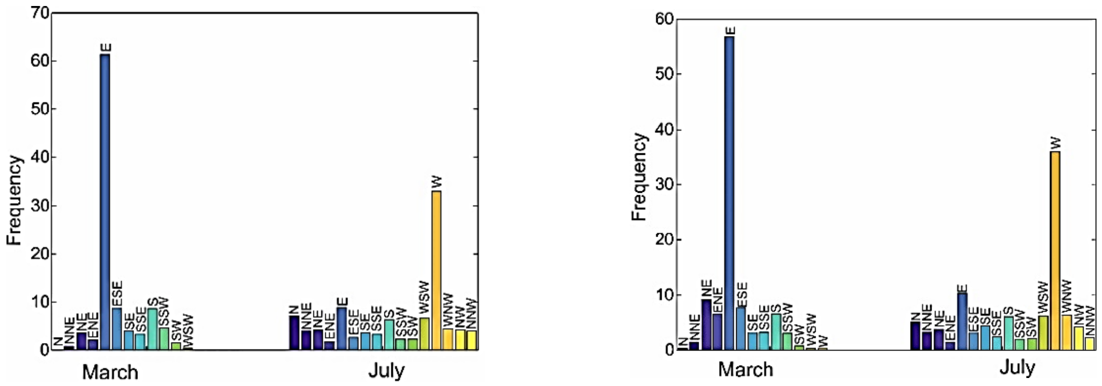
(a) (b)

Figure 3. Plots comparing monthly skewness and kurtosis of the wind speed values for (a) Herkalou and (b) Lake Assal

Table 2 presents the wind direction for each corresponding frequency for the selected months which are March (in cold season) and July (in hot season), represented by a dashed line in Figures 2(a) and (b). In March, for both locations, the eastern winds coming from the sea were predominant, with a maximum frequency that exceeded 50%. In July, the second dominant sector is the western winds, namely Khamsin which is a sandstorm characterized as a hot and dry dusty base wind coming from Ethiopia, the neighboring country of Djibouti. Figure 4 depicts the other wind directions' sectors for the same months.

Table 2. Wind direction and frequencies were observed for selected months over the studied period

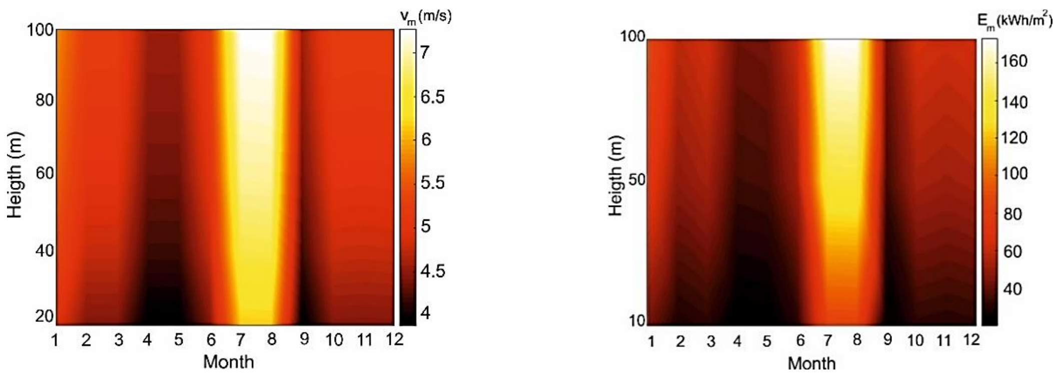
Wind direction	Herkalou Frequency (%)		Lake Assal Frequency (%)	
	March	July	March	July
E	61.36	8.91	56.81	10.39
W	0.01	33.11	0.29	36.05



(a) (b)

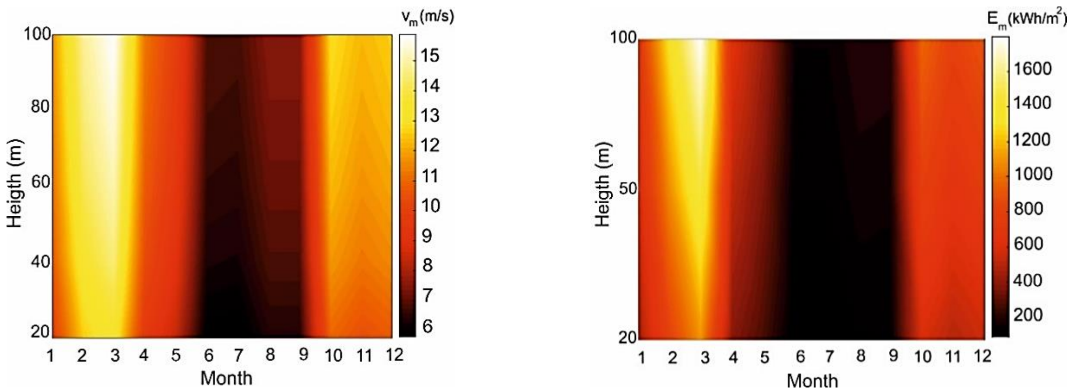
Figure 4. Detailed frequencies for the main prevailing wind direction were observed for (a) Herkalou and (b) Lake Assal

Figures 5 and 6 illustrate the distribution of the monthly variations of V_m and E_m for the different heights at Herkalou and Lake Assal sites. It can be observed that the wind energy higher than 160 kWh/m^2, while at Lake Assal it is approximately 1700kWh/m^2 at 100 m height above ground level. It is instructive to point out that for the Herkalou site, the wind speed values are high in the hot period between May and September. V_m values varying from 6.5 m.s^{-1} (at 20 m in July) until 7.5 m.s^{-1} (at 100 m in August). Based on the wind classification [32], with the wind speed data classified under 4.5–5.5 m.s^{-1} class and the wind power values range between 50 W/m^2 and 200 W/m^2, Herkalou site is included in class 1 (Poor) but it is suitable for small wind turbines installation.



(a) (b)

Figure 5. Variations of the monthly average (a) V_m and (b) E_m for the different heights at Herkalou



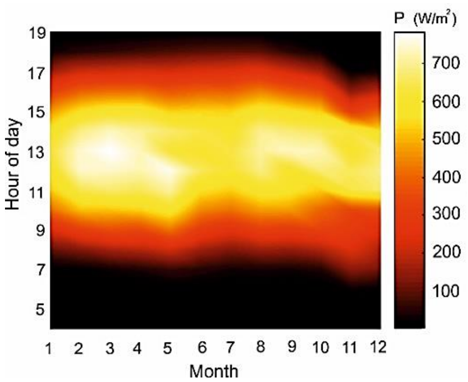
(a) (b)

Figure 6. Variations of the monthly average (a) V_m and (b) E_m for the different heights at Lake Assal

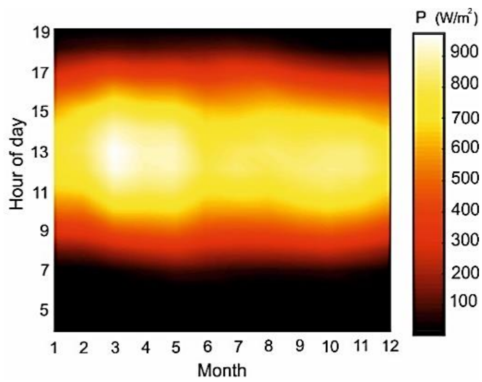
It can be seen also, that the Lake Assal site shows low values of the V_m and E_m in the hot period at all heights. The Lake Assal site is associated with high wind speed values varying between 12 m.s^{-1} (at 20 m) to 16 m.s^{-1} (at 100 m). However, based on the wind resources category, it plainly concluded that wind resources in the Lake Assal location are falling into class 7 (Excellent) for all months except for the hot season in June and July which is into class 1 (Poor). It can further be proposed that the site has an exploitable potential for wind energy and can contribute to wind power development.

For each location, the distribution of the hourly and monthly mean solar radiation is displayed in Figure 7. The figures show a similar distribution and a constantly high level of solar radiation throughout the year, with the monthly maximum global radiation peaks of around 900 W/m² between 11:00 and 14:00 pm for both sites. In Figure 7(a), for Herkalou, the month of March had the highest monthly mean solar radiation of 800 W/m^2 at 13:00 pm, but the month of July shows the lowest monthly mean solar radiation of 670.5 W/m^2, coinciding with the hot and dry season. In Figure 7(b), for the Lake Assal, the graph shows that the maximum monthly mean solar radiation of 1100 W/m^2 was recorded in March at 13:00 pm, while the lowest mean solar radiation of 700 W/m^2 was recorded in June at 12:00.

Figure 8 shows the monthly mean of global solar horizontal irradiation for Herkalou and Lake Assal. The highest monthly mean of global solar irradiation values was 5.29 kWh/m2.day-1 and 6.90 kWh/m^2.day-1 in March for Herkalou and Lake Assal, respectively. On the other side, the lowest monthly mean of global solar irradiation values was 4.03 kWh/m^2.day-1 (November) and 5.13 kWh/m^2.day-1 (December) for Herkalou and Lake Assal, respectively.



(a)



(b)

Figure 7. Distribution of the hourly and monthly mean solar radiation for (a) Herkalou and (b) Lake Assal

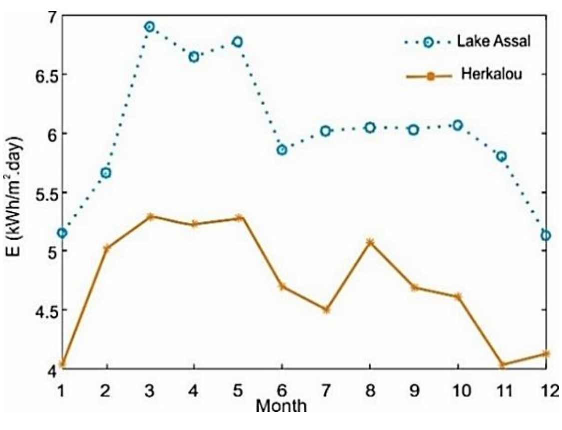


Figure 8. Monthly mean of measured global solar irradiation

Due to Djibouti's proximity to the equator, the angle of incidence of radiation is relatively high all year round. The only when the global high level of solar radiation decreases somewhat is during the cool season (from October to December). The clearness index is lower in the cool-season and varies between 0.38 and 0.4. However, even during these periods where the locations receive minimum solar radiation (about 4-6 kWh/m². day^{-1}), the country has an opportunity to develop solar energy applications.

4. CONCLUSION

Djibouti has a very hot and humid climate all year round due to the city's proximity to the sea. The results are the first approach, allowing to have a better view of the measured wind profile and solar radiation on the sites of Herkalou and the Lake Assal for an estimate of the wind and solar energy potential. According to the monthly mean variations of measured wind speed, the Lake Assal site is associated with high wind speed values varying from 12 $m.s^{-1}$ (at 20 m) to 16 $m.s^{-1}$ (at 100 m) in the cool season, with a monthly average wind energy value of 1700 kWh/m^2 at 100 m height above ground level. While Herkalou site shows the wind speed values vary from 6.5 $m.s^{-1}$ (at 20 m) to 7.5 $m.s^{-1}$ (at 100 m). It can be concluded that the Herkalou site has an encouraging potential to develop a wind power application throughout the month. On the other hand, for both sites, the average monthly share of direct radiation is on average 65%. With total global radiation of 2,898 $kWh/(m^2.$ year), this type of climate receives the greatest amount of solar radiation compared to other places in the world. Results obtained in this study will be useful to implement renewable energy in the country and are favorable to deploy the solar and wind technologies for the studied locations.

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