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Evaluation of Wind Potential for an Optimum Choice of Wind Turbine Generator on the Sites of Lomé, Accra, and Cotonou Located in the Gulf of Guinea

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ABSTRACT. This work presents the characterization and assessment of wind energy potential in annual and monthly levels of the sites of Lomé, Accra and Cotonou located in the Gulf of Guinea, and the optimal characteristics of wind turbines to be installed on these sites. Studies of characterization and the wind potential of these sites from the wind speed data collected over a period of thirteen years at a height of 10 meters above the ground, show an annual average speed of 3.52 m/s for Lomé, 3.99 m/s for Cotonou and 4.16 m/s for Accra. These studies also showed that a monthly average speed exceeding 4 m/s was observed on the sites of Cotonou and Accra during the months of February, March, April, July, August and September and during the months of July, August and September on the site of Lomé. After a series of simulation conducted using the software named PotEol that we have developed in Scilab, we have retained that the wind turbines rated speeds of ~8 to 9 m/s at the sites of Lomé and Cotonou and ~ 9 to 10 m/s on the site of Accra would be the most appropriate speeds for optimal exploitation of electric energy from wind farms at a height of 50 m above the ground.

Keywords: Modeling, Wind potential, Optimal parameters choice, Wind turbine generator

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1. Introduction

Today, with the exhaustion of the world stock of oil, energy demand ever increasing, and the fear of increasingly alarming pollution, renewable energy sources (solar, wind etc.) are seen as ideal, clean, and inexhaustible sources of energy (Impacts et al., 2007; Sahin, 2004).

In the event that the increase in energy consumption could be offset by wind energy (clean energy), mastery of this energy is essential. The electrical energy from wind power is produced by the kinetic energy of the wind. Wind parameters vary in time and space (Sahin, 2004). Therefore, the study of the characterization of the wind distribution for different sites should be considered when installing wind energy conversion systems (Burton et al., 2001), (Ajavon et al., 2015), (Lu et al., 2002). So if conversion systems were well adapted to the site, an

assessment of the wind potential and a prediction of the power produced would be made with reasonable accuracy on the site (Tong, 2010).

Several studies have shown that the Weibull distribution function is better suited to characterize the distribution of the wind on a site (Sahin, 2004; Kaldellis and Zafirakis, 2011; Manwell et al., 2002; Akdag and Dinler, 2009; Ahmed, 2013). A recent study on the site of Lomé (Togo) confirmed that the hybrid Weibull distribution function is recommended for a better fit of the distribution of wind speeds at the site where the frequency of calm winds is important (Salami et al., 2013).

In this work, the distributions of wind speeds are characterized, the optimal choice of turbines is determined, and the production of electrical energy of the three sites in the Gulf of Guinea (Lomé, Togo, Accra in Ghana and Cotonou in Benin) is evaluated. Also, changes

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in statistical parameters of the series of wind speeds and variations of recoverable and produced energy are analyzed for each month. For an accurate wind energy assessment, we have developed a software tool named PotEol to determine the characteristics of the wind, assess the wind potential, and make optimal parameters choice of a wind turbine.

2. Data source

Wind data series on the three sites involved in this study were obtained through meteorological databases of the University of Wyoming (Department of Atmospheric Science)(<http://Wheather.uwyo.edu/surface/meteogra> m/, n.d.).

The data were recorded daily by one-hour interval (this is the average over the 10 minutes before the hour)

at a height of 10 m above the ground. For this study we are particularly interested the wind speed and time of recording. The data cover the period from January 2000 to October 2012 for Lomé, Togo (where the measuring point is located at 6.17N, 1.25E, 25 meters) and from January 2000 to December 2012 for Accra, Ghana (where the measurement point is located at 5.60N 0.17W, 69 meters) and Cotonou, Benin (where the measuring point is located at 6.35N 2.38E, 9 meters). The geographical location of the three (03) sites is presented in Figure 1.

The application of statistical methods on the data collected allowed us to model the distribution of wind speeds, to assess wind energy potential, and to make an optimum choice of wind turbines parameters suitable for each site.

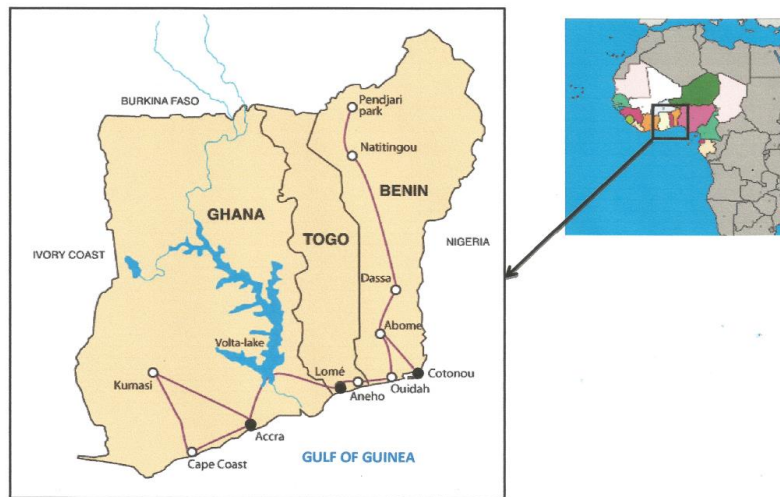


Fig. 1 Location of the study sites

3. Methods

In this section, we briefly introduce the hybrid Weibull function used to characterize the distribution of wind speeds, the methods used for the assessment of wind energy potential and the optimal choice of a wind turbine parameters on the three sites studied.

3.1. Weibull Hybrid distribution

The expression of the Hybrid Weibull function is given by Equation (1).

$$f(V) = \begin{cases} F_0 & \text{if } V < 1 \text{ m/s} \\ (1-F_0) \left(\frac{K}{C}\right) \left(\frac{V}{C}\right)^{K-1} \cdot \exp\left[-\left(\frac{V}{C}\right)^K\right] & \text{if } V \geq 1 \text{ m/s} \end{cases} \quad (1)$$

where:

- F_0 represents the frequency of calm winds, which is determined from the wind data.

In this work, the values of K parameters (shape parameter) and C (scale parameter [m/s]) of the distribution was determined by the least squares method (Sahin, 2004; Celik, 2004; WD, 1996; Bagiorgas *et al.*, 2011; Rocha *et al.*, 2012).

The average speed V_{moy} following the Weibull hybrid function is given by Equation (2)

$$V_{\text{moy}} = (1-F_0)C \cdot \Gamma\left(1 + \frac{1}{K}\right) \quad (2)$$

where:

- Γ is the gamma function.

3.2. Wind potential

The wind potential of a site is defined as the extractable energy during a given period of operation of

a given wind turbine on this site, (Stankovic *et al.*, 2009; Editorial, 2011; Jowder, 2009). It is therefore a function of the distribution of wind speeds and the windfarm characteristics installed on the site.

The assessment of wind energy potential must take into account the operating height of the wind turbine used. Generally, the wind speed is measured at a height of 10 meters above the ground (Z_0). To determine the characteristics of the distribution of wind speeds at heights above 10 m above ground, extrapolation of the parameters K and C of the hybrid Weibull distribution is evaluated using the method of Justus (Justus and Mikhail, 1976; Justus *et al.*, 1978). Thus, if C_1 and K_1 are the hybrid Weibull parameters, respectively scale and shape parameters at a height Z_1 , then these parameters at a height Z_2 would be obtained from Equations (3) and (5).

$$C_2 = C_1 \left(\frac{Z_2}{Z_1} \right)^N \tag{3}$$

With

$$N = \frac{[0.37 - 0.0881 \cdot \ln(C_1)]}{\left[1 - 0.0881 \cdot \ln\left(\frac{Z_1}{10}\right) \right]} \tag{4}$$

And

$$K_2 = \frac{K_1}{\left[1 - 0.0881 \cdot \ln\left(\frac{Z_2}{Z_1}\right) \right]} \tag{5}$$

Since the kinetic energy of the wind is converted into mechanical energy, the available energy undergoes losses in cascades, until the output energy is released at end the conversion machine (Betz limit, machine thresholds, and conversion losses) (Sahin, 2004).

The average kinetic energy available on a site, per unit time and unit area is expressed by the Equation (6):

$$P = \frac{1}{2} \rho \int_0^{+\infty} V^3 f(V) dV = \frac{1}{2} \rho \overline{V^3} = \frac{1}{2} \rho C^3 \Gamma\left(1 + \frac{3}{K}\right) \tag{6}$$

where:

- ρ is the density of air (kg m⁻³),
- V is the wind speed, and
- $f(V)$ is the distribution function of hybrid Weibull (Equation (1)).

The speed of the wind at the downstream of the wheel being never zero, it is assumed that the wind power is not completely recovered at the propeller. Only a portion of the available average power density is recovered. It is expressed by the Equation (7) (Lu *et al.*, 2002).

$$P_{rec} = C_p P \tag{7}$$

where:

- C_p is the aerodynamic power coefficient of the machine.

According to Betz, the theoretical maximum aerodynamic power coefficient of the machine C_{pmax} is equal to 16/27 or 59.26%. To reach such numbers is extremely difficult. Aerodynamic power coefficients of the best machines today barely reach 50.00% (Sahin, 2004).

3.3 Optimal choice of the parameters of a wind turbine

The variation in power supplied to a load given by a wind turbine provided with a speed regulating device as a function of wind speed, is shown in Figure 2.

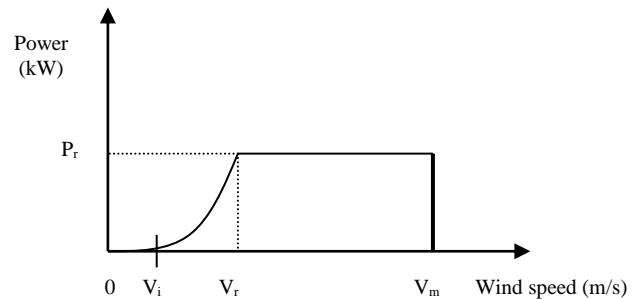


Fig. 2 Energy Power curve of a wind turbine

As presented in Figure 2, V_m is the speed beyond which the wind turbine has to be stopped to prevent damage; V_i is the starting speed for which the turbine provides energy; and V_r is the rated speed of the wind turbine. Beyond the rated speed V_r , the control system maintains the power constant and equal to the nominal power.

This curve allows the deduction of the following expressions (Equation (8)) of the power P :

$$P = \begin{cases} 0 & \text{if } V < V_i \\ P_1(V) & \text{if } V_i < V < V_r \\ P_r & \text{if } V_r < V < V_m \\ 0 & \text{if } V > V_m \end{cases} \tag{8}$$

This power is simple expression except in the interval $]V_i, V_r[$. In this interval, the expression of the power can be approximated by a polynomial of degree n .

Knowing the distribution function of wind speeds $f(V)$ and the wind turbine's power curve on the site, the

average output power P_{moy} is given by Equation (9) (Salami *et al.*, 2013; Al Zohbi *et al.*, 2015).

$$P_{moy} = \int_{V_i}^{V_r} P_1(V) f(V) dV + P_r \int_{V_r}^{V_m} f(V) dV \quad (9)$$

where the expression of the power $P_1(V)$ can be approximated by Equation (10).

$$P_1(V) = a_1 + b_1 V^K \quad (10)$$

with:

$$\frac{P_{moy}}{P_r} = (1 - F_0) \left[\left(\frac{V_r}{C} \right)^K - \left(\frac{V_i}{C} \right)^K \right]^{-1} \left\{ \exp \left[- \left(\frac{V_i}{C} \right)^K \right] - \exp \left[- \left(\frac{V_r}{C} \right)^K \right] \right\} - \exp \left[- \left(\frac{V_m}{C} \right)^K \right] \quad (13)$$

with the rated power of the wind turbine as expressed by Equation (14).

$$P_r = \eta_{moy} V_r^3 \quad (14)$$

where:

- η_{moy} represents the average performance of the wind turbine.

Thus, the problem of choosing the parameters of a wind turbine on a site can be formulated as an optimization problem according to the Equation (15).

$$\begin{cases} (\hat{V}_r, \hat{V}_i) = \arg(\max P_{moy}(V_r, V_i)) \\ V_r \geq mV_i \end{cases} \quad (15)$$

where:

- \hat{V}_r and \hat{V}_i represent the estimated nominal and optimum start speeds of the wind turbine,
- m is a positive real number.

Figure 3 shows that an optimal choice of wind turbines parameters on a site is to utilize the maxima of the average power curves produced by the wind turbines on this site. For example, in this figure a wind turbine with a rated speed as twice as its starting speed ($V_r = 2V_i$) would produce a maximum average power at the site where the average wind speed of this site is half of the rated speed of the wind turbine.

$$a_1 = \frac{P_r V_i^K}{(V_i^K - V_r^K)} \quad (11)$$

$$b_1 = \frac{P_r}{(V_r^K - V_i^K)} \quad (12)$$

where:

- K is the form factor of hybrid Weibull distribution.

Replacing $f(V)$ from Equation (9) by its full expression, we get the wind load factor on the site by Equation (13).

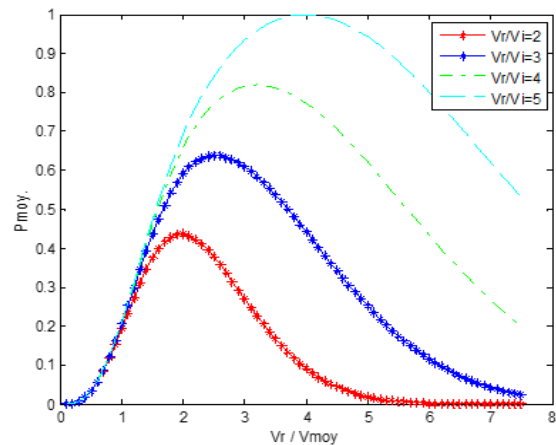


Fig. 3 Average power curves produced for different types of wind turbines

4. Data processing

The determination of the parameters of the distribution function of wind speeds, the optimal choice of turbines and the evaluation of the potential for a wind farm given by the methods mentioned previously in this work requires the use of a computer tool for significant time savings, accurate and reliable results. To do so, we have developed a computer application called PotEol (acronym of "Potentiel Eolien") that will help us process the wind data. The computer application PotEol is developed using Scilab to perform the wind data processing. In this article we will discuss only the results provided by this computer application.

PotEol has a graphical interface that allows the user to interact with the application. The main chart of the application PotEol is shown in Figure 4. The software accesses the database of a given site, distributes wind

speed data following the month, calculates power densities available (using equation (6)) and recoverable (Betz limit) (using equation (7)) and evaluates the wind farm generation on the given site. The application PotEol provides the wind speed histogram and its fitting Weibull curve; the hybrid Weibull parameters and other statistical parameters are sought. The results are given numerically (data tables) and graphically (curves and histograms).

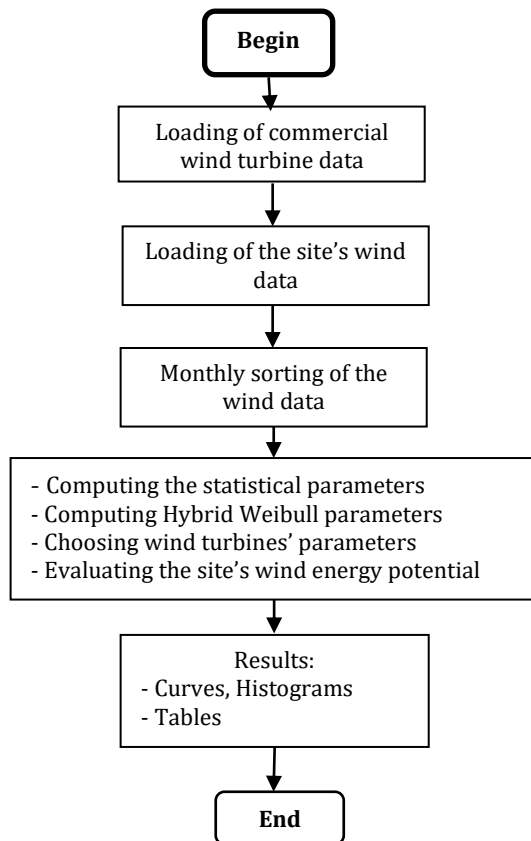


Fig. 4 Main Organization Chart of PotEol

PotEol has a database with a non-exhaustive list of commercial wind turbines. A commercial wind turbine is designated on the main window PotEol as a wind turbine that the user can choose to simulate the production of electricity on the wind site. Each commercial wind turbine is characterized by its rated power, rated speed, and the length of its blades, its starting speed, maximum speed and power curve.

Furthermore, the use of this application allows the user to characterize the distribution of wind speeds, assess the wind potential available from meteorological data for a given site. In addition, the application could determine the optimal wind turbine parameters suitable for optimal production of electrical energy from wind on the site according to relation (15). Thus, the optimal parameters obtained can be retrieved by the user from the main window PotEol for a wind turbine to simulate the production of electricity on a wind farm optimally.

For the remainder of this work, the application PotEol was used to calculate statistical parameters, model the distribution of wind speeds, select optimal parameters of wind turbines, and assess the wind energy potential monthly and annually for the three sites (Lomé, Accra, and Cotonou).

5. Results and Discussion

PotEol was applied and based on weather data of the sites Lomé site, Accra site, and Cotonou site yielded the results and discussion that are presented in this section.

5.1. The statistical parameters of wind speeds data

After loading the weather data of a site, the statistical parameters of wind speeds of this site were obtained. The parameters obtained for each site are: number of samples, minimum speed, maximum speed, average speed, standard deviations, flattening coefficients (kurtosis), the asymmetry coefficients (skewness), the variation coefficients and hybrid Weibull adjustment function parameters (K , C and F_0).

The results for the three (03) studied sites, (Lomé site, Accra site, and Cotonou site) are presented.

5.1.1. The Lomé site

Table 1 shows the results of the calculated monthly and yearly statistical parameters of Lomé site.

From the statistical results of Table 1 it was observed that:

- the minimum value of hourly wind speed was 0 m/s for all months of the year;
- the maximum speed of 16 m/s was recorded during the month of April;
- only the month of July, August, and September had an average speed greater than 4 m/s and the maximum monthly average speed of 4.666 m/s was recorded for the month of August;
- the standard deviation values were between 1.780 (recorded during the month of December) and 2.161 (recorded during the month of March);
- a maximum kurtosis of 2.679 was recorded for the month of May and minimum kurtosis of 2.267 for the month of February;
- the speeds series of July and August presented lower coefficients of asymmetry (skewness) whereas a strong dissymmetry was recorded during the month of May;
- most variation coefficients (except for the months of July, August, and September) are greater than 0.5 which is the turbulence threshold.

Consequently, it can be observed, from Table 1, that the Lomé site had a low and turbulent wind conditions. According to the Pacific Northwest National Laboratory (PNNL) classification system (Keyhani *et al.*, 2010),

Lomé site with annual mean wind speed value of 3.520 m/s fall outside of the category if based on the year round wind speed. This means that under the current wind turbine technology, this area may not be suitable for year round large-scale electricity generation due to

the cost factor. However for small-scale applications, and in the long run with the development of wind turbine technology, the utilization of wind energy is still promising.

Table 1

Results of the calculation of statistical parameters monthly and yearly scale for Lomé site data

Periods	Numbers of samples	V _{moy} (m/s)	V _{min} (m/s)	V _{max} (m/s)	Standard deviation (m/s)	Skewness (-)	Kurtosis (-)	Coef. of Variation (-)	C (m/s)	K (-)	F ₀ (%)
January	10992	2.758	0	9	1.798	0.482	2.632	0.651	3.560	1.963	8.843
February	10220	3.320	0	12	2.096	0.213	2.267	0.561	4.505	2.212	4.325
March	11488	3.948	0	10	2.161	0.150	2.286	0.547	4.805	2.115	4.370
April	10701	3.640	0	16	2.126	0.322	2.594	0.584	4.564	1.982	4.934
May	11534	3.012	0	13	1.959	0.519	2.679	0.650	3.887	1.925	7.092
June	11114	3.138	0	12	1.933	0.466	2.623	0.616	4.044	2.046	5.498
July	11167	4.209	0	11	1.953	0.088	2.433	0.463	5.103	2.594	1.737
August	11239	4.666	0	13	1.822	0.026	2.562	0.390	5.713	3.065	0.516
September	11477	4.098	0	10	2.019	0.169	2.374	0.492	5.046	2.478	1.889
October	11935	3.231	0	13	1.985	0.460	2.532	0.614	4.141	2.099	4.633
November	10444	2.952	0	9	1.822	0.371	2.343	0.617	3.803	2.116	5.619
December	10990	2.820	0	9	1.780	0.370	2.386	0.631	3.62	2.047	7.425
Annual	133304	3.520	0	16	2.040	0.308	2.423	0.581	4.382	2.086	4.725

5.1.2. The Accra site

Table 2 presents the results of the calculation of monthly and yearly statistical parameters of Accra site.

The following observations and comments can be made from the statistical results of Table 2:

1. the minimum value of hourly wind speed was 0 m/s for all months of the year;
2. the maximum speed of 21 m/s was recorded during the month of July;
3. the month of August presented an average speed greater than 5 m/s;
4. the standard deviation values were between 1.994 (recorded during the month of December) and 2.359 (recorded during the month of April);
5. a maximum kurtosis of 3.885 was recorded for the month of January and a minimum of 2.267 for the month of February;
6. the speeds series of the months of September and August had the lower coefficients of asymmetry (skewness) whereas a strong dissymmetry were recorded during the month of January;
7. most variation coefficients were greater than 0.5 which is the turbulence threshold.

Based on previous observations from Table 2, it can be said that the Accra site presented turbulent wind conditions. According to the Pacific Northwest National Laboratory (PNNL) classification system (Keyhani *et al.*, 2010), Accra site with annual mean wind speed value of

4.160 m/s fall outside of the category if based on the year round wind speed. This means that under the current wind turbine technology, this area may not be suitable for year round large-scale electricity generation due to the cost factor. However for small-scale applications, and in the long run with the development of wind turbine technology, the utilization of wind energy is still promising.

5.1.3. The Cotonou site

Table 3 shows the results of the calculation of monthly and yearly statistical parameters of the Cotonou site.

For the Cotonou site, the following observations and comments can be made from the statistical results of Table 3:

- the minimum value of hourly wind speeds was 0 m/s for all months of the year;
- a maximum speed of 14 m/s was recorded during the month of October;
- the month of August recorded the greatest average speed (4.968 m/s);
- the standard deviation values were between 1.472 (recorded during the month of August) and 1.879 (recorded during the month of June);
- a maximum kurtosis of 3.281 was recorded for the month of January and minimum kurtosis of 2.394 for the month of February;
- the speeds series of the months of March and September had the lower coefficients of

asymmetry (skewness) whereas a strong dissymmetry were recorded during the month of May;

- most variation coefficients were smaller than 0.5 (the turbulence threshold).

Table 2
Results of the calculation of statistical parameters monthly and yearly scale Accra site data

Periods	Numbers of samples	V _{moy} (m/s)	V _{min} (m/s)	V _{max} (m/s)	Standard deviation (m/s)	Skewness (-)	Kurtosis (-)	Coef. of Variation (-)	C (m/s)	K (-)	F ₀ (%)
January	6355	3.503	0	21	2.114	0.327	3.885	0.603	4.292	1.628	9.772
February	5105	4.323	0	11	2.228	0.032	2.498	0.515	5068	2.116	5.544
March	6070	4.206	0	13	2.249	0.113	2.478	0.534	4.915	2.126	5.684
April	5624	4.155	0	13	2.359	0.139	2.436	0.567	4846	1.973	7.432
May	5679	3.701	0	16	2.208	0.247	2.806	0.596	4.472	1.836	9.051
June	5090	3.921	0	15	2.187	0.079	2.571	0.557	4,634	1.970	7.701
July	6210	4.842	0	21	2.092	-0.083	3.264	0.432	5882	2.165	3.285
August	6385	5.087	0	18	2.014	-0.190	3.342	0.395	6040	2.393	3.195
September	5546	4.937	0	11	2.101	-0.195	2.826	0.425	5745	2.373	3.552
October	4834	4.187	0	19	2.191	0.120	2.954	0.523	5071	1.949	5.792
November	5707	3.548	0	18	2.024	0.263	3.333	0.570	4.406	1.804	8.200
December	6127	3.475	0	14	1.994	0.218	2.709	0.573	4.246	1.985	7.850
Annual	68732	4.160	0	21	2.215	0.088	2.766	0.532	4.993	1.894	6.412

Table 3
Results of the calculation of monthly and yearly statistical parameters of Cotonou site

Periods	Numbers of samples	V _{moy} (m/s)	V _{min} (m/s)	V _{max} (m/s)	Standard deviation (m/s)	Skewness (-)	Kurtosis (-)	Coef. of Variation (-)	C (m/s)	K (-)	F ₀ (%)
January	11818	3.193	0	9	1.611	0.074	2.486	0.504	3.991	2.424	4.282
February	10648	4.347	0	11	1.720	-0.382	2.628	0.395	5.135	2.853	1.193
March	11336	4.636	0	10	1.679	-0.490	2.855	0.362	5.440	3.010	0.820
April	10987	4.260	0	13	1.814	-0.159	2.862	0.425	5.204	2.541	1.866
May	11185	3.543	0	13	1.806	0.239	2.876	0.509	4.579	2.289	2.834
June	11001	3.687	0	11	1.879	0.049	2.448	0.509	4.502	2.309	3.863
July	11074	4.859	0	11	1.694	-0.403	3.138	0.348	5.701	2.934	1.156
August	10931	4.968	0	10	1.472	-0.294	3.281	0.296	5.910	3.387	0.659
September	10780	4.483	0	9	1.816	-0.419	2.793	0.405	5.356	2.479	2.570
October	11525	3.435	0	14	1.787	0.103	2.489	0.520	4.352	2.216	3.766
November	11340	3.403	0	12	1.578	-0.075	2.518	0.463	4.286	2.503	2.787
December	11803	3.267	0	11	1.510	-0.083	2.394	0.462	4.107	2.606	2.66
Annual	134428	3.993	0	14	1.812	-0.109	2.535	0.453	4.864	2.482	2.391

Based on the observations from Table 3, it can be said that turbulent wind conditions prevailed on the Cotonou site. According to the Pacific Northwest National Laboratory (PNNL) classification system (Keyhani *et al.*, 2010), Cotonou site with annual mean wind speed value of 3.993 m/s fall outside of the category if based on the year round wind speed. This means that under the current wind turbine technology, this area may not be suitable for year round large-scale electricity generation due to the cost factor. However for small-scale applications, and in the long run with the development of wind turbine technology, the utilization of wind energy is still promising.

5.2. Evaluation of wind energy potential

The assessment of wind energy potential is accurate if the wind characteristics used are determined under optimum conditions.

An optimal choice of wind turbines parameters on a site, should take it into consideration the height of the wind generator since the wind farm potential is a function of the height.

5.2.1. Changes in available power densities and recoverable depending on the height of the tower

Densities of recoverable and available powers on a monthly scale were calculated for different towers

heights (10 m, 30 m and 50 m) for the three sites, to study the changes on sites as a function of the height.

The histograms of Figures 5, 6 and 7 show the changes in available power densities on a monthly scale on the first studied site (the Lomé site), respectively at 10 m, 30 m and 50 m height.

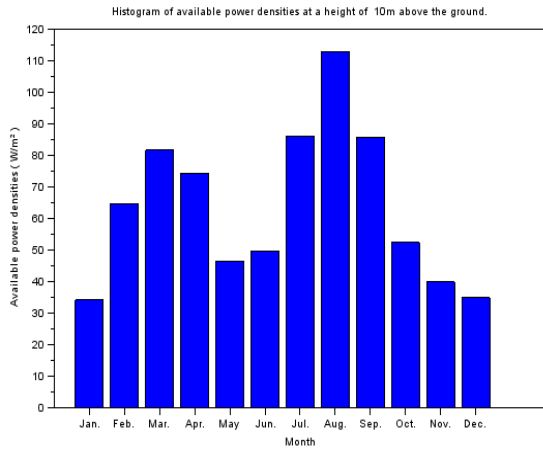


Fig. 5 Histogram of available power densities respectively at 10 m height on the Lomé site

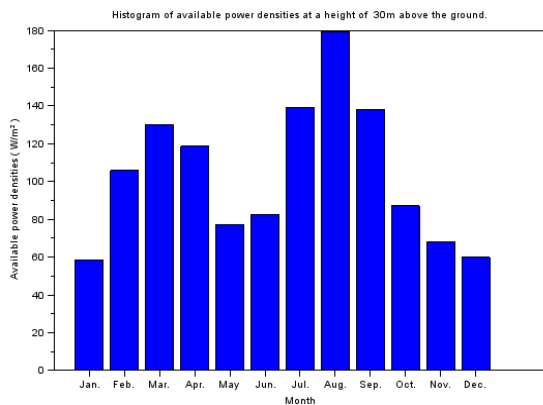


Fig. 6 Histogram of available power densities respectively at 30 m height on the Lomé site

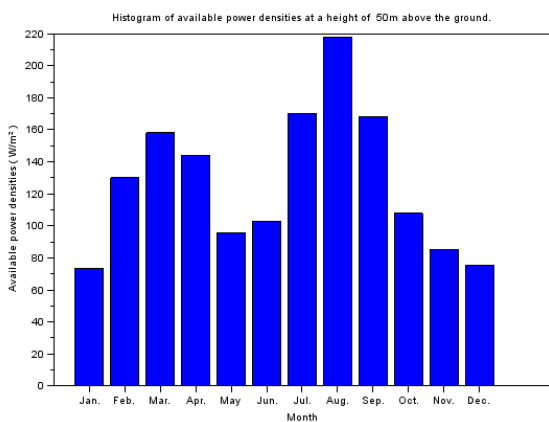


Fig. 7 Histogram of available power densities respectively at 50 m height on the Lomé site

The histograms of Figures 8, 9 and 10 show the changes in available power densities on a monthly scale

on the second studied site (the Accra site), respectively at 10 m, 30 m and 50 m height.

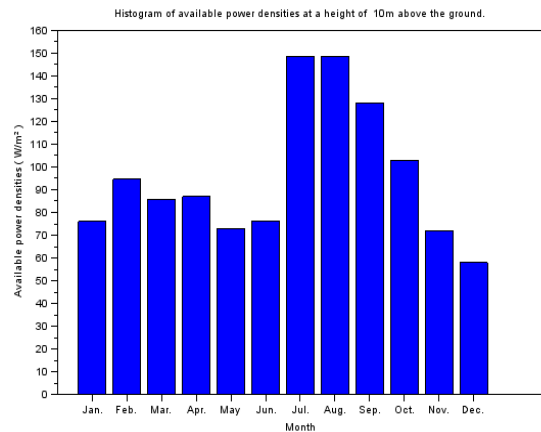


Fig. 8 Histogram of available power densities respectively at 10 m height on the Accra site

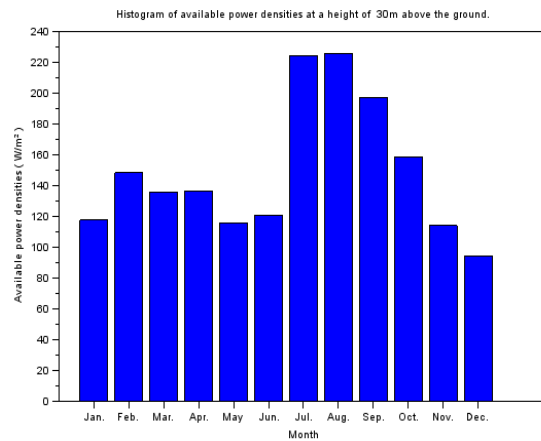


Fig. 9 Histogram of available power densities respectively at 30 m height on the Accra site

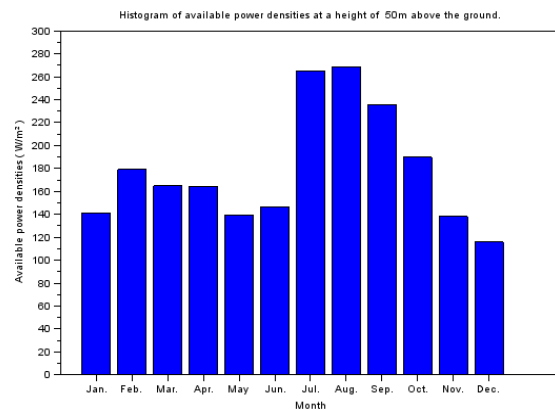


Fig. 10 Histogram of available power densities respectively at 50 m height on the Accra site

The histograms of Figures 11, 12 and 13 show the changes in available power densities on a monthly scale on the third studied site (the Cotonou site), respectively at 10 m, 30 m and 50 m height.

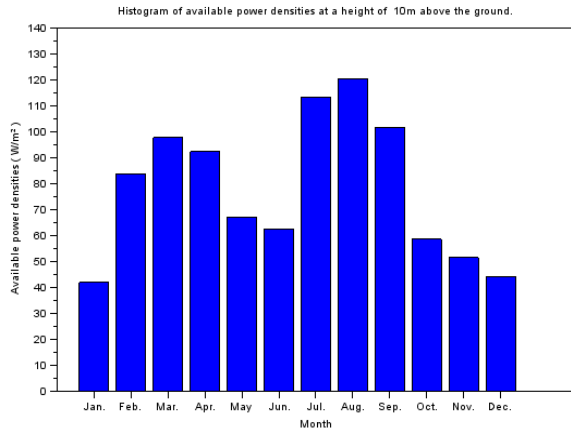


Fig. 11 Histogram of available power densities respectively at 10 m height on the Cotonou site

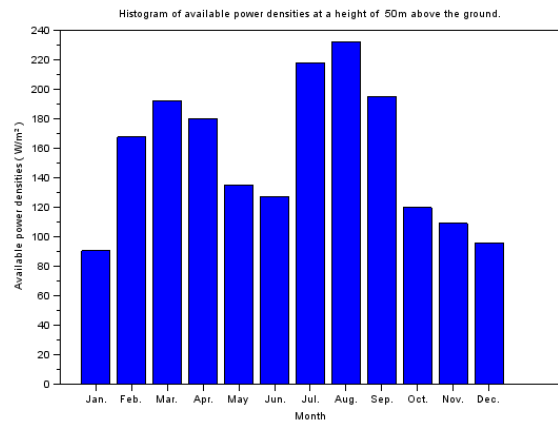


Fig. 13. Histogram of available power densities respectively at 50 m height on the Cotonou site

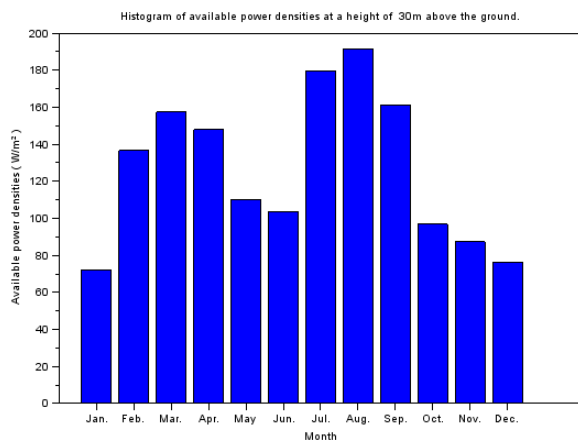


Fig. 12 Histogram of available power densities respectively at 30 m height on the Cotonou site

From the histograms of Figures 5, 6 and 7, we found that the recoverable power densities on the Lomé site increased with the tower height. Additionally, the month of August had the highest power density available and January had the smallest. The minimum and maximum power densities available on a monthly scale on the Lomé site for different heights are respectively about:

1. ~34 W/m² and ~112 W/m² for a tower height of 10 m;
2. ~58 W/m² and ~179 W/m² for a tower height of 30 m;
3. ~73 W/m² and ~217 W/m² for a tower height of 50 m.

Table 4

Power densities available and recoverable for the Lomé site, Accra site and Cotonou site at a height of 50 m above the ground

	Lomé		Accra		Cotonou	
	Available power density (W/m ²)	Recoverable power density (W/m ²)	Available power density (W/m ²)	Recoverable power density (W/m ²)	Available power density (W/m ²)	Recoverable power density (W/m ²)
January	73.562	43.592	141.364	83.771	90.685	53.739
February	130.157	77.130	179.012	106.081	167.707	99.382
March	158.060	93.669	164.713	97.608	192.133	113.857
April	144.260	85.491	164.558	97.516	180.100	106.726
May	95.501	56.593	139.688	82.778	135.149	80.088
June	102.571	60.782	146.348	86.725	127.378	75.483
July	169.933	100.701	264.939	157.001	217.643	128.974
August	217.592	128.943	268.196	158.931	231.736	137.325
September	168.153	99.646	235.848	139.762	194.723	115.391
October	108.009	64.005	190.045	112.619	119.661	70.910
November	85.402	50.608	137.978	81.765	108.997	64.591
December	75.513	44.748	115.999	68.740	96.061	56.925
Annual	125.357	74.286	185.786	110.095	152.162	90.170

The Accra site is windier than the Lomé site. The minimum and maximum power densities available on a monthly scale on the Lomé site for different heights are respectively about (see Figures 8, 9 and 10):

1. ~56 W/m² and ~148 W/m² for a tower height of 10 m;
2. ~94 W/m² and ~225 W/m² for a tower height of 30 m;

3. $\sim 115 \text{ W/m}^2$ and $\sim 268 \text{ W/m}^2$ for a tower height of 50 m.

Similarly, the values of the minimum and maximum power densities available on a monthly scale on the Cotonou site according to the height are respectively about (see Figures 11, 12 and 13):

1. $\sim 41 \text{ W/m}^2$ and $\sim 120 \text{ W/m}^2$ for a height of 10 m tower;
2. $\sim 72 \text{ W/m}^2$ and $\sim 191 \text{ W/m}^2$ for a height of 30 m tower;
3. $\sim 90 \text{ W/m}^2$ and $\sim 231 \text{ W/m}^2$ for a height of 50 m tower.

Table 4 shows the power densities available and recoverable on the three sites at a height of 50 m above the ground.

It can be noted that there was an uneven distribution of recoverable power densities on a monthly scale at the three sites, which was due to seasonal effects.

Yu and Qu (2010) noted that sites of good or excellent resource potential, with the wind power density above 400 W/m^2 or even reach 800 W/m^2 at a height of 50 m, and wind speed more than 7.0 m/s , are suitable candidates to locate the wind power plants. According to (Yu *et al.* (2010)) the three sites are not suitable for large-scale electric wind application. But, small-scale wind turbines could be good option for Lomé, Accra and Cotonou sites in order to supply power for lightings, electric fans, chargers and air conditioning

units for small houses like proposed by (Mostafaeipour *et al.* (2011)) for Shahrabak city in Iran.

5.2.2. Optimal choice of the parameters of the wind turbine

To show the importance of a wind turbine design, we randomly chose in a database with a non-exhaustive list of commercial wind turbines one wind turbine. A wind turbine chosen is a wind turbine from the Manufacturer AUROVILLE ENERGY PRODUCT, INDIA (rated power = 5 kW, nominal speed = 14 m/s , and starting speed = 3.3 m/s) which we named in this study "wind turbine A". Thus, we could compare the load factors and average power produced by wind turbine which is the wind turbine adapted to the site with those produced by a wind turbine ("wind turbine A") we are randomly chosen.

The corresponding power curve of "wind turbine A" selected is given in Figure 14.

In Figure 14, it can be seen that the curve of the adjustment function which characterizes the production of the wind turbine in the starting speed range and nominal speed ($[V_i, V_r]$), had parameters which were estimated with a MSE error of $5.3 \cdot 10^{-9}$ and a correlation coefficient R^2 of 0.9. Therefore from Equation (8), we can express the model of the energy power curve of this wind turbine by Equation (16):

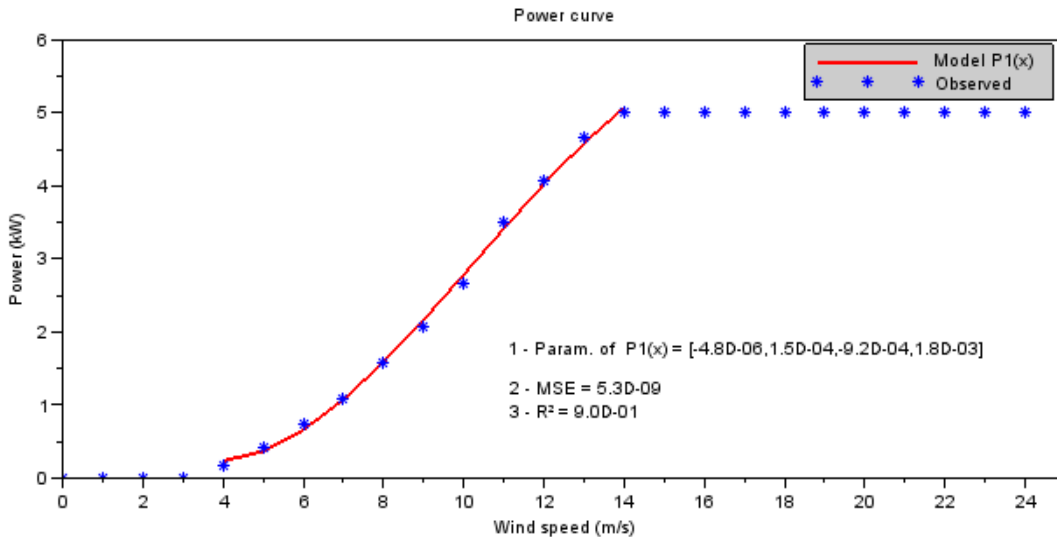


Fig. 14 Power curve of the selected wind turbine A (AUROVILLE AEP 5000)

$$P(V) = \begin{cases} 0 & \text{if } V < 3.3 \text{ m/s} \\ -4.8 \cdot 10^{-6} V^3 + 1.495 \cdot 10^{-4} V^2 - 9.162 \cdot 10^{-4} V + 1.8 \cdot 10^{-3} & \text{if } 3.3 \text{ m/s} < V < 14 \text{ m/s} \\ 5 & \text{if } 14 \text{ m/s} < V < 25 \text{ m/s} \\ 0 & \text{if } V > 25 \text{ m/s} \end{cases} \quad (16)$$

For the optimal choice of wind turbines parameters on the three sites, the height of the towers was set to 50 meters above the ground. From the wind data at 10 m above ground at the site, the PotEol software determined the hybrid Weibull monthly and yearly scale parameters at a height of 50 m above the ground and graphed the normalized average power curves produced by different types of wind turbines (Figure 3) using Equation (13).

In this study, we used normalized average powers produced curve. This curve corresponded to a range of wind turbines with a rated speed (V_r) as twice as the starting speed (V_i). This involved solving the optimization problem of the relation (15) with the constraint $V_r = 2V_i$ ($m = 2$). Thus, for the constraint $V_r = 2V_i$, the maximum of the curve produced average power was obtained for $V_r = 1.7V_{moy}$ on the Lomé site (Figure 15).

The corresponding theoretical optimum characteristics of the wind turbine are $V_r = 8.276$ m/s and $V_i = 4.138$ m/s. We therefore chose the standard parameters $V_r = 8$ m/s and $V_i = 4$ m/s for this site. We named in this study the optimum wind turbine for Lomé site with parameters $V_r = 8$ m/s and $V_i = 4$ m/s “wind turbine B”.

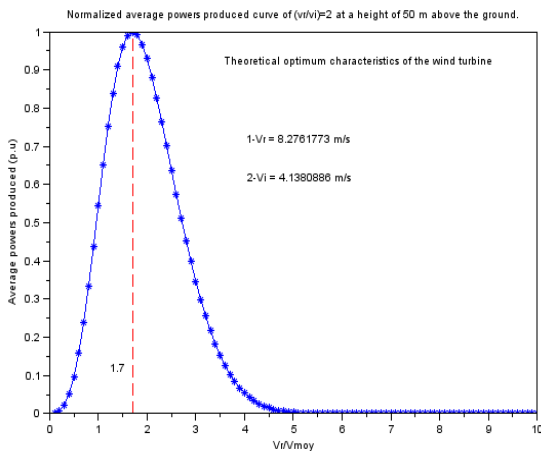


Fig. 15 Normalized average powers produced curve on Lomé site for $V_r = 2V_i$

The corresponding theoretical optimum characteristics of the wind turbine are $V_r = 8.276$ m/s and $V_i = 4.138$ m/s. We therefore chose the standard parameters $V_r = 8$ m/s and $V_i = 4$ m/s for this site. We named in this study the optimum wind turbine for Lomé site with parameters $V_r = 8$ m/s and $V_i = 4$ m/s “wind turbine B”.

For the site of Accra, we obtained for $V_r = 1.8V_{moy}$ (Figure 16) that the theoretical optimal characteristics

of the wind turbine corresponded to $V_r = 9.617$ m/s and $V_i = 4.808$ m/s. Consequently, we chose the standard parameters of $V_r = 10$ m/s and $V_i = 5$ m/s for this site. We named in this study the optimum wind turbine for Accra site with parameters $V_r = 10$ m/s and $V_i = 5$ m/s “wind turbine C”.

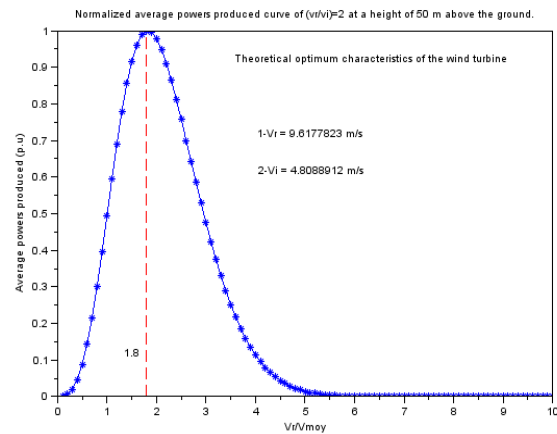


Fig. 16 Normalized average powers produced curve on Accra site for $V_r = 2V_i$

The results for the site of Cotonou are: $V_r = 8.228$ m/s and $V_i = 4.114$ m/s, $V_r = 1.5V_{moy}$ (Figure 17). We chose the standard parameters $V_r = 8$ m/s and $V_i = 4$ m/s for this site. We named in this study the optimum wind turbine for Cotonou site with parameters $V_r = 8$ m/s and $V_i = 4$ m/s “wind turbine D”.

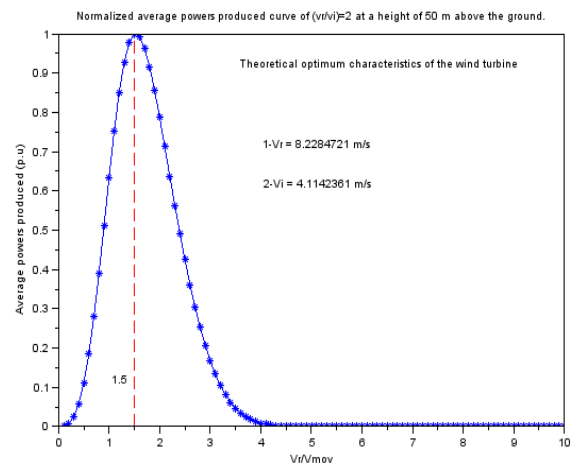


Fig. 17 Normalized average powers produced curve on Cotonou site for $V_r = 2V_i$

The optimum parameters of the wind turbine (for $V_r = 2V_i$) obtained for each site were used to evaluate the wind energy potential.

Tables 5 and 6 show the average power produced by this optimal wind turbine selected, load factors, the monthly and annual scale of the Lomé site for the constraint $V_r = 2V_i$.

The “wind turbine A” on the Lomé site produces an annual average power density of 32.485 W/m², with an efficiency of 43.729% from the Betz limit and a low load factor of 12.757% against an average power density of 46.212 W/m², 62.208% efficiency from the Betz limit, with a load factor of 26.618% for the “wind turbine B”.

The “wind turbine A” on the site of Accra produces an annual average power density of 45.152 W/m², with an of 41.011% from the Betz limit and a low load factor of 17.731% against an average power density of 67.613 W/m², a yield of 61.413% from the Betz limit, with a load factor of 24.816% for the “wind turbine C”;

The “wind turbine A” on the site of Cotonou produces an annual average power density of 38.863 W/m², with an efficiency of 43.099% from the Betz limit and a low load factor of 15.211% against an average

power density of 56.230 W/m² with an efficiency of 62.359% from the Betz limit and a load factor of 32.956% for the “wind turbine D”.

From simulation results, we can conclude that “wind turbine A” which is randomly selected is not adapted to the three sites, because its efficiencies from the Betz limit were smaller than 50%. The optimal wind turbines obtained for Lomé site (“wind turbine B”), for Accra site (“wind turbine C”) and for Cotonou site (“wind turbine D”), have efficiency from the Betz limit higher than 50%. Optimal wind turbines with rated speeds around 8 m/s to 10 m/s (small size wind turbines) confirmed that the three sites have poor wind resource potential. This study indicates that small wind turbine projects at the three sites are feasible (Mostafaeipour A. *et al.*, 2011).

Table 5
 Average power generated by wind turbines (Case $V_r = 2V_i$) on the three sites

	Lomé		Accra		Cotonou	
	Power densities produced by the “wind turbine A” (W/m ²)	Power densities produced by the “wind turbine B” (W/m ²)	Power densities produced by the “wind turbine A” (W/m ²)	Power densities produced by the “wind turbine C” (W/m ²)	Power densities produced by the “wind turbine A” (W/m ²)	Power densities produced by the “wind turbine D” (W/m ²)
January	20.297	26.820	35.451	50.781	24.104	33.172
February	33.784	47.826	44.868	66.020	42.644	61.769
March	39.921	58.483	41.908	60.858	48.422	70.693
April	36.541	53.358	41.771	60.392	45.206	66.708
May	25.533	34.888	36.226	50.800	34.639	50.110
June	27.094	37.606	37.902	53.617	33.145	47.199
July	42.963	63.040	60.158	98.501	54.196	80.312
August	54.154	79.751	62.867	99.727	57.964	84.492
September	42.368	62.169	56.896	87.665	48.539	71.987
October	28.292	39.887	56.150	69.901	31.084	44.010
November	22.840	31.542	35.395	50.089	28.463	40.236
December	20.585	27.444	30.944	42.626	25.176	35.581
Annual	32.485	46.212	45.152	67.613	38.863	56.230

Table 6
 Load factors for wind turbines (Case $V_r = 2V_i$) on the three sites

	Lomé		Accra		Cotonou	
	Load factor of the “wind turbine A” (%)	Load factor of the “wind turbine B” (%)	Load factor of the “wind turbine A” (%)	Load factor of the “wind turbine C” (%)	Load factor of the “wind turbine A” (%)	Load factor of the “wind turbine D” (%)
January	7.970	25.427	13.921	19.226	9.465	34.408
February	13.267	30.252	17.619	26.810	16.746	36.628
March	15.677	26.245	16.457	26.841	19.015	35.438
April	14.350	23.525	16.403	24.716	17.752	32.238
May	10.026	24.934	14.226	22.951	13.602	28.917
June	10.639	27.319	14.884	24.846	13.016	29.350
July	16.871	31.838	23.742	25.350	21.283	36.196
August	21.266	34.815	24.687	28.396	22.762	41.708
September	16.638	32.670	22.340	28.749	19.061	33.111
October	11.110	26.494	18.123	24.158	12.206	29.893
November	8.969	26.891	13.899	22.857	11.177	33.028
December	8.083	28.206	12.151	24.849	9.886	32.311
Annual	12.757	26.618	17.731	24.816	15.261	32.956

6. Conclusion

The current investment in wind power operation is quite expensive compared to conventional energy sources, with the risk of no return on investment. It is therefore imperative to conduct extensive feasibility studies before the establishment of a wind farm. In this regard, we have characterized and assessed the wind energy potential, and studied the optimal choice of wind turbines for annual and monthly scales of the Lomé site, Accra site and Cotonou site located in the Gulf of Guinea.

We evaluated the wind potential at the annual and monthly scale for the sites of the Lomé site, Accra site and Cotonou site located in the Gulf of Guinea. The results showed that these three sites have in general a low wind potential. Also from our study we found that the monthly distribution of the wind on the three sites is not uniform. Thus the months of February, March, April, July, August and September are recommended over other months, for a more profitable operation of the wind farm energy on the three sites. Given the low energy potential on the three sites, wind turbines with low rated speeds of approximately 8 m/s to 9 m/s on the Lomé site and Cotonou site, and around 9 m/s to 10 m/s on the Accra site would be most appropriate for optimum exploitation of electric energy from wind farms on these sites from a height of 50 m above the ground.

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