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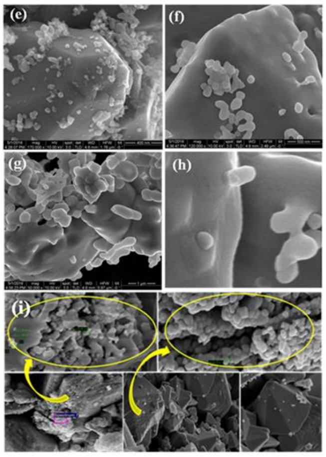

Figure 7 of 14

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by Hagninou Elagnon Venance Donnou, Aristide Barthélémy Akpo, Gbènoukpo Fidèle Nonfodji and Basile Bruno Kounouhewa

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Variability of Onshore Wind Energy Potential in the 60 m above the Ground under Convective Atmosphere in Southern Benin

Hagninou Elagnon Venance Donnou*, Aristide Barthélémy Akpo, Gbènoukpo Fidèle Nonfodji, Basile Bruno Kounouhewa

Laboratoire de Physique du Rayonnement (LPR), Faculté des Sciences et Techniques (FAST), Université d'Abomey-Calavi, 01 B.P.526, Cotonou, Benin
*Corresponding author: donhelv@yahoo.fr

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Abstract The variability of onshore wind energy potential has been investigated over Cotonou coast (Benin) under an unstable atmosphere. Data on the speed and the wind direction at 10 m above the ground recorded every 10 min, have been used over the period from June 2011 to April 2014. The power law based on atmospheric stability was used to determine the vertical wind profile. The Weibull function was used to characterize the frequency distribution of the wind speed and to calculate the wind energy potential. The results indicate that the annual average of the wind speed for a typical day time varies from 3.8 ± 0.40 $m.s^{-1}$ (10 m) to 7.25 ± 0.58 $m.s^{-1}$ (60 m) during the convective diurnal cycle. The mean parameters k and c of Weibull were evaluated respectively from 1.65 (December) to 2.21 (August) and from 4.3 (December) to 9.1 $m.s^{-1}$ (August). The most frequent wind speeds at the study site are between 2.5 ± 0.56 $m.s^{-1}$ in December to 7 ± 0.24 $m.s^{-1}$ in August from 10 to 60 m. The average wind speeds giving the maximum energy vary from 6.91 ± 0.56 $m.s^{-1}$ in December at 10 m to 12.20 ± 0.24 $m.s^{-1}$ in August at 60 m. Finally, the wind energy potential has been evaluated. As a result, the largest quantity of energy are generally collected between 13:00 UTC and 18:00 UTC. During the months of March, July and August, the daily energy peaks are observed between 14:00 UTC and 18:00 UTC with the values of the order of 650 to 770 $W.m^{-2}$ at 60 m. The average annual energy potential has been estimated at 130.43 $W.m^{-2}$ (10 m) and 332.67 $W.m^{-2}$ (60 m). In view of these results, the site of Cotonou could be suitable for the installation of small and large wind turbines in order to supply the southern Benin with power energy.

Keywords: *wind energy, convective atmosphere, vertical wind profile, wind speed, Weibull function*

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1. Introduction

Energy plays a significant role in human and economic development and its demand is growing exponentially in the world [1]. Due to the progressive exhaustion of the traditional energy resources and their use, which contributes significantly to environmental pollution [2,3,4,5], the part of renewable energies in the world's energy portfolio has constantly increased [6]. Among all sources of renewable energies, wind power due to its safety for the environment as well as its sustainability, has become more visible in recent years [3]. Electricity generated from the wind turbines has therefore grown remarkably over the past two decades [7]. The cumulative installed wind capacity worldwide increased from 23,900 MW in 2001 to 539,581 MW in 2017, with a growth rate of about 2000% which deserves to be valorized in developing countries [8,9] in particular Benin. Moreover the electricity production in rural communities is an acute problem militating against socioeconomic well-being of the population of these underdeveloped countries [10].

Several studies have focused on the evaluation of the wind energy potential in the world. In Africa the studies of [11] in Morocco, of [12,13,14] in Algeria, the studies of [15,16] in South Africa, the studies of [4,10,17-27] in Nigeria, those of [24,28] in Cameroon and of [29,30,31,32,33] in Ghana, the researches of [32,33,34] in Togo, of [35,36,37] in Senegal and of [38] in Niger and Mali clearly show the importance given to this source of renewable energy by researchers. In Benin, according to the studies of [33,39,40,41] at 10 m, the authors are unanimous to recognize that south of Benin has a significant wind energy resources the long of the Atlantic ocean. This resource could reduce the country's energy dependence on foreign evaluated to 70% and increase its low rate of rural electrification (6.3%) [42]. This altitude of 10 m is nevertheless insufficient for a large-scale production. The ignorance of this deposit at the wind turbine hub height is therefore a handicap to the development of this source of energy in our region of study.

To overcome these difficulties, the research focused on the wind speeds extrapolation from standard measurement point of 10 m to the height of the wind turbine hub. The studies of [32] have therefore tried to resolve this problem in using the models of [43,44] to determine the wind energy power at an altitude varying from 10 m to 50 m on our study site. However the studies of [45] showed that this model and others, evaluated on the site do not suitably reproduce the vertical profile of wind. The authors therefore suggested the establishment of a specific model for each site. For the site of Cotonou, they have therefore determined the best-fitting equations obtained from the radiosondage data collected on the study site between 10 and 60 m based on the power and logarithmic law. These equations were revealed more suitable in the site of Cotonou and have been used in this study.

The purpose of this study is therefore to evaluate the wind energy potential in Cotonou between 10 m and 60 m above the ground and to study its variability during the convective diurnal cycle.

2. Material and Methods

2.1. Material

2.1.1. Study Area

Benin is situated in the Gulf of Guinea from latitude 6° 15’ N to 12° 30’ N and longitude 1° E to 3° 40’ E. Its coastal zone 125 km long is characterized by a succession of lakes and lagoons separated from the sea by a narrow coastal strip [46] (Figure 1).

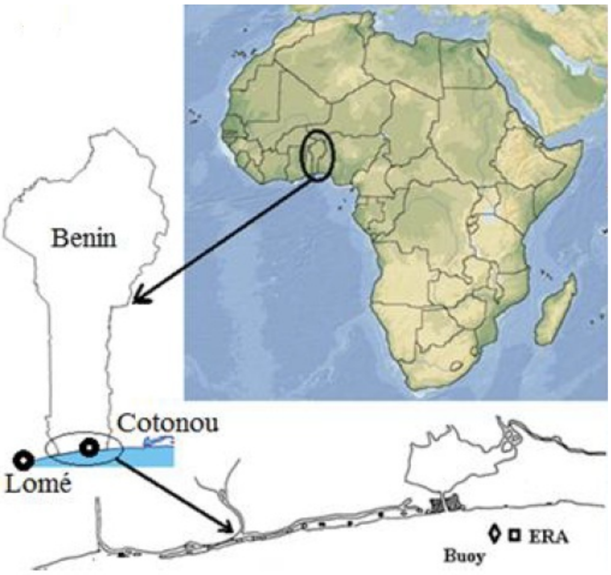

Figure 1. Geographical situation of the coastal zone of Benin. Location on the map of Africa [47]

2.1.2. Data Collection

In this study we used meteorological data of wind collected during the project Millennium Challenge Account compact I (MCA) in southern Benin in Cotonou coast (at the Port Authority platform). Wind speed and its direction have been recorded on the site every 10 min, using a cup anemometer and weather vane installed at 10 m during the period of June 2011 to April 2014. Figure 2 shows an overview of the wind observation system installed on the Port Authority platform, located in Cotonou.

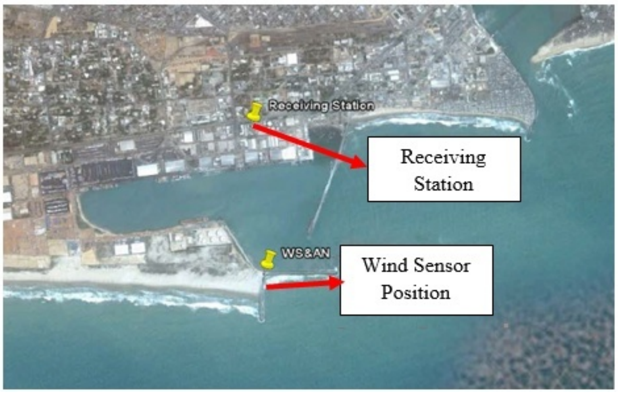

Figure 2. Location of wind sensor and the receiving station in the seaside [48]

2.2. Methods

2.2.1. Statistical Distribution Analyses of Wind Speed Data

In bibliography, various statistical distributions exist for describing and analyzing wind resources data. Some of these include normal and lognormal, Rayleigh and Weibull probability distributions [17,49,50]. On our study site, [51] showed that the distribution of Weibull has been found to be suitable in analyzing and representing the frequency distribution of wind. This distribution has therefore been used and it expresses as follows [20,22,51,52,53]:

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

$k \succ 0, v \succ 0, c \succ 0$

where k is the Weibull shape parameter, c is the scale parameter, v is the wind speed and $f(v)$ is the probability of observing wind speed. The Weibull cumulative density function $F(v)$ corresponding is given as [17]:

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

The expression of average wind speed $\bar{v}$, cubic speed average $\bar{v}^{3}$ and standard deviation σ in function of Weibull parameters are presented as followed:

$$\bar{v} = c\Gamma\left(1 + \frac{1}{k}\right) \tag{3}$$

$$\overline{v^3} = c^3 \Gamma\left(1+\frac{3}{k}\right) \tag{4}$$

$$\sigma^2 = c^2\left[\Gamma\left(1+\frac{2}{k}\right) - \Gamma^2\left(1+\frac{1}{k}\right)\right]. \tag{5}$$

Γ is gamma function. It expresses by:

$$\Gamma(x) = \int_0^\infty \exp(-t)\, t^{x-1} dt \tag{6}$$

Several methods are used to determine Weibull parameters. The one used in this study to calculate the shape parameter k is given by the following approximation [54,55]:

$$k = 0.83\left(\bar{v}\right)^{0.5}. \tag{7}$$

The scale factor is determined by:

$$c = \frac{\bar{v}}{\Gamma\left(1+\frac{1}{k}\right)}. \tag{8}$$

The most probable (v_{mp}) and maximum energy carrying (v_{Emax}) wind speeds are expressed as [19]:

$$V_{mp} = c\left(\frac{k-1}{k}\right)^{1/k} \tag{9}$$

$$V_{E\max} = c\left(\frac{k+2}{k}\right)^{1/k}. \tag{10}$$

2.2.2. Extrapolation of Wind Speed at Different Hub Height

In Cotonou, the studies of [45] performed from the radiosonde data on the site of Cotonou airport have showed that the log-linear law and the power law are suitable to characterize the vertical profile of wind speed. The authors have therefore proposed the best fitting equations of wind profile in the lower 60 m of the surface boundary layer. From the power law that requires less parameters of wind shear (roughness length z_0 and Obukhov length L), they have determined the wind speed profile under a convective atmosphere (between 09:00 UTC and 18:00 UTC). This law was proposed by [56] and reported by [57,58,59]:

$$\frac{v_h}{v_1} = \left(\frac{z}{z_1}\right)^\alpha \tag{11}$$

where v_1 is wind speed at 10 m (z_1) over the ground, v_h is wind speed at the wind turbine hub height, z is the wind turbine hub height. This law depends only on a single parameter α which is the wind friction or Hellman exponent, also known as wind shear coefficient. From the works of [60] and for an unstable atmosphere, α can be also computed by:

$$\alpha = \frac{\left(1-16\frac{z}{L}\right)^{-1/4}}{\ln\left(\frac{(\eta-1)(\eta_0+1)}{(\eta+1)(\eta_0-1)}\right) + 2Arc\tan(\eta) - 2Arc\tan(\eta_0)} \tag{12}$$

$$\eta = \left(1-16\frac{z}{L}\right)^{1/4} \tag{13}$$

$$\eta_0 = \left(1-16\frac{z_0}{L}\right)^{1/4}.. \tag{14}$$

From Equations (11-14), the vertical profile of wind obtained on our study site under convective atmosphere by [45] is presented in Figure 3. In this study these wind profiles were used to evaluate the wind power energy between 10 m and 60 m.

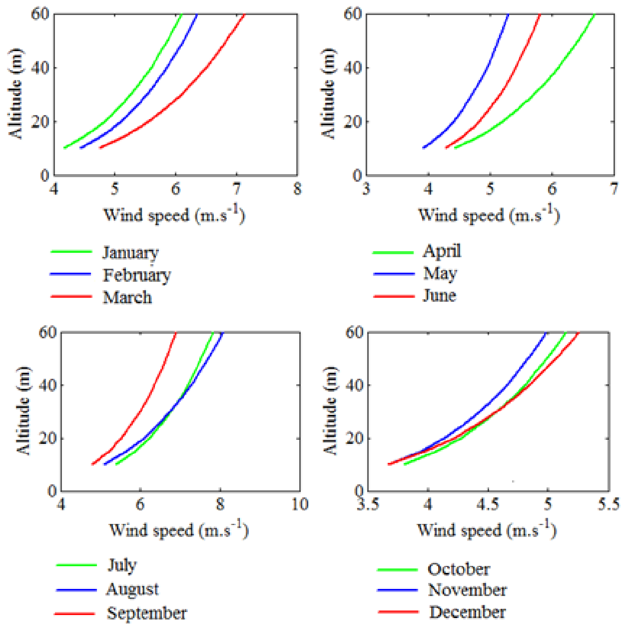

Figure 3. Average vertical profile of wind convective diurnal cycle at monthly scale [45]

2.2.3. Wind Power Density

The power density of the wind power is the most significant characteristic of the wind [1]. It represents the quantity of energy produced by the wind. The Weibull wind power density per unit area can be obtained from [17,19,20]:

$$P = \frac{1}{2}\rho c^3 \Gamma\left(1+\frac{3}{k}\right). \tag{15}$$

where P is the wind power (W.m^{-2}) and ρ is the air density at the site.

3. Results and Discussion

3.1. Wind Speed Distribution

Figure 4 and Figure 5 are present the wind distribution during the convective diurnal cycle

Figure 4 shows that the distribution of wind speeds during the convective diurnal cycle does not present the same variations from one month to the next. During the months of February, March, April, September, October, November, December, we note a gradual increasing of the wind speed from 09:00 UTC to 18:00 UTC. However, in November there is a slight decrease in the wind speed between 16:30 UTC and 18:00 UTC. It ranges from

2.7 $m.s^{-1}$ in October-November to 5.9 $m.s^{-1}$ in March at 10 m and from 3.59 $m.s^{-1}$ in November to 8.8 $m.s^{-1}$ in March at 60 m. During the months of July, August it is noticed that the wind speed varies very little during the day. The values recorded are high and vary from 4.73 $m.s^{-1}$ at 10 m to 8.60 $m.s^{-1}$ at 60 m in July. In January, there are two wind peaks during the convective diurnal cycle. A first less visible peak is observed around 10:00 UTC and the second most pronounced around 17:20 UTC. From 09:00 UTC to 10:00 UTC there is a slight increase of the wind speed and from 10:00 UTC to 12:30 UTC, its intensity decreases. Thereafter it increases again to reach its second peak around 17:20 UTC. At 10 m the two peaks are estimated respectively to 4.24 $m.s^{-1}$ and 4.96 $m.s^{-1}$ and at 60 m to 6.1 $m.s^{-1}$ and 7.14 $m.s^{-1}$ respectively. During the month of June, the wind amplitude increases from 09:00 UTC to 16:00 UTC and decreases thereafter until 18:00 UTC. The peak is reached with a speed of 5.34 $m.s^{-1}$ at 10 m and 7.33 $m.s^{-1}$ at 60 m. In May the variation of the wind during the diurnal cycle is slightly ascending with fluctuations around the average value of the wind estimated at 4.21 $m.s^{-1}$ and 5.57 $m.s^{-1}$ at 60 m. The months of July and August are the windiest of the year due to the strengthening of local breezes by the West African Monsoon [61,62]. The average speeds respectively have been estimated to 5.43 $m.s^{-1}$, 5.12 $m.s^{-1}$ (10 m) and at 7.95 $m.s^{-1}$, 8.05 $m.s^{-1}$ (60 m). During the months of November, December the average speeds are low during the year. They are evaluated respectively to 4.01 $m.s^{-1}$, 3.83 $m.s^{-1}$ (10 m) and at 5.34 $m.s^{-1}$, 5.53 ms^{-1} (60 m). This period is characterized by the gradual appearance of the harmattan causing a movement of the intertropical front (ITF) towards the south of the country justifying the low wind speeds we observed. Figure 5 illustrates the annual change in wind speed during the convective diurnal cycle. It is noted that the wind amplitude increases during the day and varies from 3.86 $m.s^{-1}$ to 5.05 $m.s^{-1}$ (10 m) and from 5.54 $m.s^{-1}$ to 7.24 $m.s^{-1}$ (60 m). This overall trend of the wind in day as confirmed by the studies of [62], can be due to the presence of sea breezes whose activity becomes intense during the day (due to sun shine). There is also a significant variation of the wind speed near the ground between 10 and 30 m. That could be due to the effect of roughness and obstacles encountered on the ground, which decreases with altitude. Morever nearly 98% of the wind speeds are greater than or equal to 3 $m.s^{-1}$ (starting speed of most wind turbines). The annual average wind speed during this cycle is estimated to 4.52 $m.s^{-1}$, 5.2 $m.s^{-1}$, 5.64 $m.s^{-1}$, 6 $m.s^{-1}$, 6.26 $m.s^{-1}$, 6.50 $m.s^{-1}$, respectively at 10 m, 20 m, 30 m, 40 m, 50 m and 60 m.

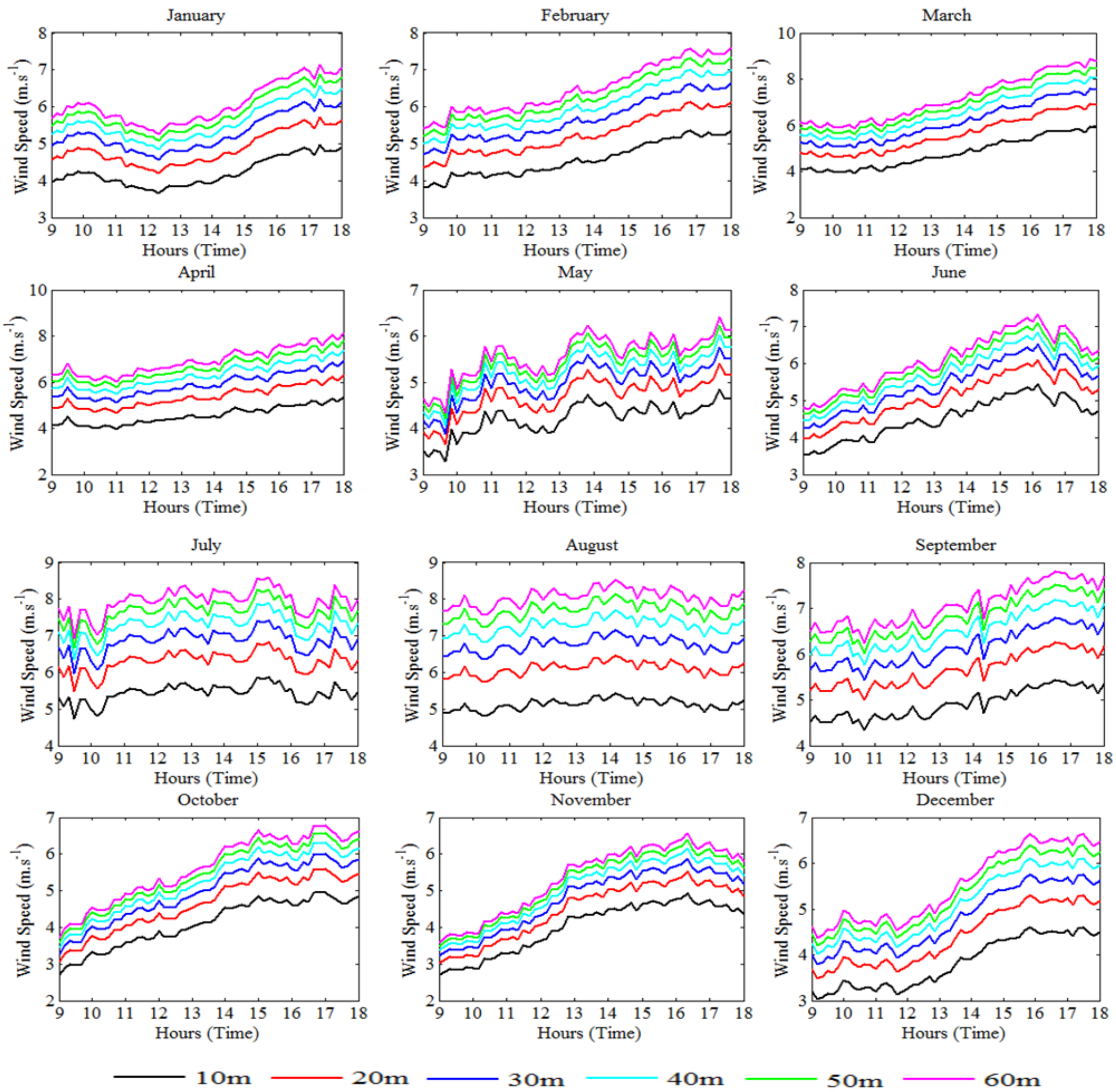

Figure 4. Daily monthly distribution of wind speed during the convective diurnal cycle (2011-2014)

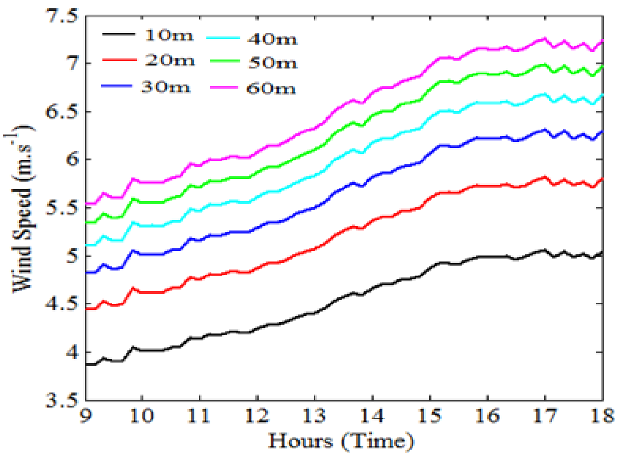

Figure 5. Annual distribution of wind speed during the convective diurnal cycle (2011-2014)

These wind speeds values obtained by this study site have been compared to those of some coastal sites of Africa more precisely in West Africa. In our study area, the studies of [32,41] during a typical day (diurnal and nocturnal cycle) have revealed that the annual average wind speeds have been respectively estimated to 3.99 $m.s^{-1}$ and 4.51 $m.s^{-1}$ at 10 m. In the coastal area of Lome and Accra, the studies of [32] have revealed that the annual wind speeds at respectively are equal to 3.5 $m.s^{-1}$ and 4.16 $m.s^{-1}$ at 10 m. On the Ghana coastal sites of Adafoah, Anloga, Aplaku, Mankoadze, Oshiyie, Warabeba, [29] showed that the annual mean wind speeds are respectively evaluated to 5.30 $m.s^{-1}$, 4.50 $m.s^{-1}$, 4.75 $m.s^{-1}$, 4.51 $m.s^{-1}$, 3.88 $m.s^{-1}$ and 4 $m.s^{-1}$ at 12 m during a typical day. In Nigeria, according to the studies of [27] on the coastal sites of Calabar, Uyo, Warri and Ikeja, the maximum mean monthly wind speeds for a typical day were respectively evaluated to 3.88 $m.s^{-1}$ in December, 4.73 $m.s^{-1}$ in January, 3.98 $m.s^{-1}$ in April, and equal to 8.37 $m.s^{-1}$ in August. On the coastal sites of Lagos and Calabar, the studies of [26] revealed that the average wind speed is about 9 $m.s^{-1}$ at 70 m on these two sites. In Senegal on the two coastal sites of Mboro and Makhana along the northern coast, the annual average wind speeds obtained during the day and night have been evaluated respectively to (4.48 $m.s^{-1}$; 3.09 $m.s^{-1}$) and (5.28 $m.s^{-1}$; 4.36 $m.s^{-1}$) par [35] at 10 m. Along the North-western of Senegal and on eight sites (Kayar, Potou, Gandon, Sine Moussa Abdou, Botla, Dara Andal, Nguebeul and Sakhor) the studies of [36,37] also showed that the mean wind speed is higher, for the day-time than for the night-time on all the sites. The wind speeds during the day is respectively estimated to 5.04 $m.s^{-1}$; 5.69 $m.s^{-1}$; 5.13 $m.s^{-1}$ at 20 m and to 5.52 $m.s^{-1}$; 5.32 $m.s^{-1}$; 5.03 $m.s^{-1}$; 5.06 $m.s^{-1}$; 4.83 $m.s^{-1}$ at 12 m. In Cameroon from the studies of [63] on three coastal sites (Kribi, Douala and Limbe) at 10 m, the results pointed out that the wind speeds at all three locations seem quite low. The average wind speeds on the three studied locations fall below 4 $m.s^{-1}$. In view of these results we therefore noticed that during the day-time, the site of Cotonou site is part of the windiest coastal regions of West Africa.

In Table 1, we present the monthly average speeds for a typical day time. Standard deviations observed on the measurements were also evaluated for each altitude.

The standard deviation increases with the wind speed and the altitude. At 10 m and 60 m, its highest value observed in November is estimated respectively to 0.7 $m.s^{-1}$, 0.93 $m.s^{-1}$. The lowest value noticed in August is estimated to 0.15 $m.s^{-1}$, 0.24 $m.s^{-1}$.

3.2. Weibull Parameters Distribution

Figure 6 and Figure 7 show Weibull parameters variation in function of altitude during convective diurnal cycle.

We noticed that the two parameters (*c* and *k*) of Weibull are an increasing function of altitude. However the shape parameter k increases very little according to the altitude unlike the scale parameter. The shape parameter k varies from 1.65 in December at 10 m to 2.2 in August at 60 m. The low values of k ($k \leq 2$) obtained indicate a narrow distribution of winds around the mean. When $k \geq 2$ and $c \geq 2$ $m.s^{-1}$, we observe a data spread [64]. The high values of k are observed during the windiest months and the low values during the least windy months. As far as the scale parameter c, it varies from 4.3 $m.s^{-1}$ in December at 10 m to 9.1 $m.s^{-1}$ in August at 60 m. The more frequent therefore the wind following in a month, the higher the Weibull parameters. This result is in agreement with the studies of [33] which esteem the Weibull parameters increase with wind frequency.

TABLE 1. Monthly average speeds of 10 to 60 m and their standard deviations in Cotonou

Months	10 m		20 m		30 m		40 m		50 m		60 m	
	$\bar{v}$	σ	$\bar{v}$	σ	$\bar{v}$	σ	$\bar{v}$	σ	$\bar{v}$	σ	$\bar{v}$	σ
Jan	4.22	0.38	4.86	0.44	5.27	0.48	5.6	0.51	5.85	0.53	6.07	0.55
Feb	4.57	0.47	5.23	0.54	5.66	0.58	5.99	0.62	6.26	0.64	6.48	0.67
Mar	4.79	0.66	5.59	0.77	6.12	0.85	6.52	0.91	6.86	0.95	7.14	0.99
Apr	4.55	0.38	5.35	0.45	5.89	0.49	6.30	0.53	6.63	0.56	6.92	0.58
May	4.21	0.35	4.69	0.39	5.00	0.42	5.23	0.44	5.41	0.45	5.57	0.47
Jun	4.52	0.55	5.08	0.61	5.44	0.66	5.71	0.69	5.92	0.72	6.11	0.74
Jul	5.43	0.24	6.29	0.28	6.86	0.31	7.29	0.33	7.65	0.34	7.95	0.35
Aug	5.12	0.15	6.10	0.18	6.76	0.20	7.27	0.21	7.69	0.23	8.05	0.24
Sep	4.91	0.32	5.65	0.37	6.14	0.40	6.50	0.42	6.81	0.44	7.06	0.46
Oct	4.10	0.65	4.63	0.74	4.97	0.79	5.23	0.83	5.44	0.86	5.62	0.89
Nov	4.01	0.70	4.48	0.78	4.78	0.83	5.00	0.87	5.19	0.90	5.34	0.93
Dec	3.83	0.56	4.41	0.64	4.80	0.69	5.09	0.74	5.33	0.77	5.53	0.80
Yearly	4.52	0.40	5.20	0.46	5.64	0.50	6.00	0.53	6.26	0.55	6.50	0.58

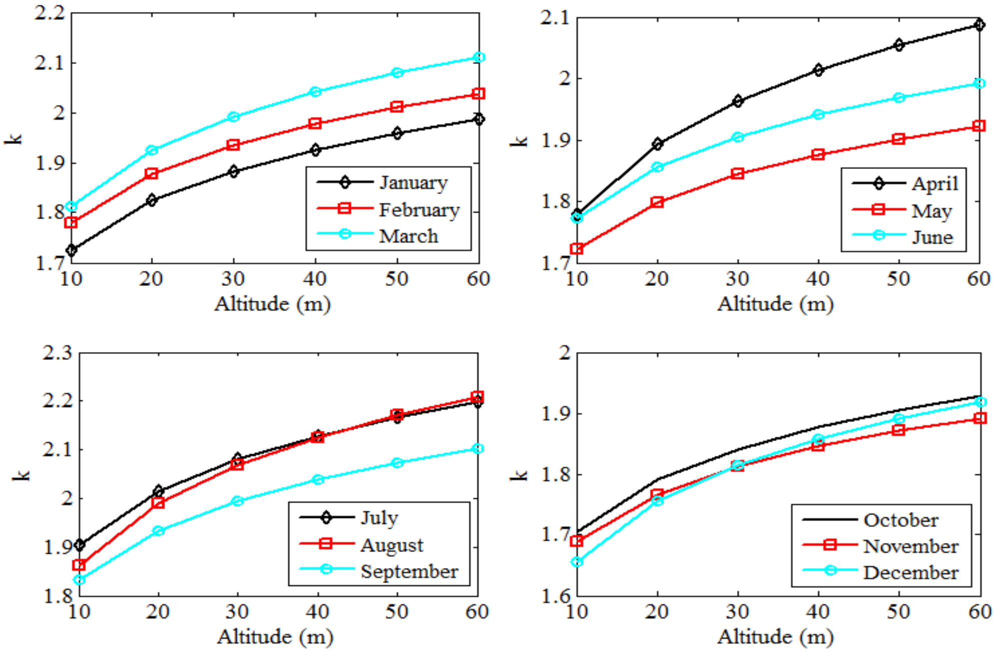

Figure 6. Variation of shape parameter k as a function of altitude (2011-2014)

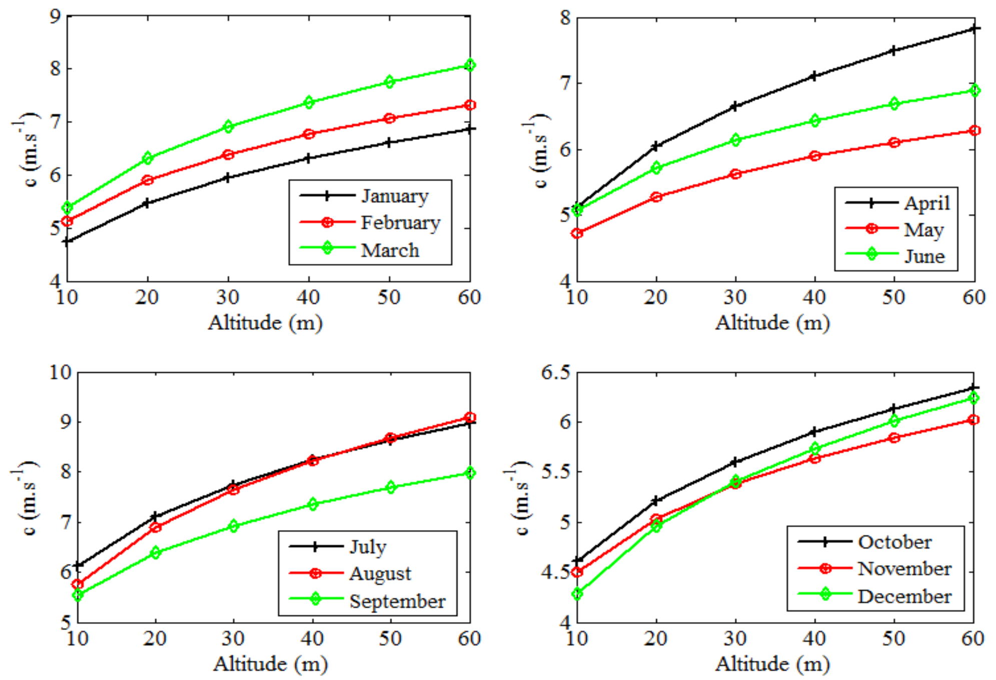

Figure 7. Variation of the scale parameter c as a function of altitude (2011-2014)

3.3. Wind Frequency Distribution

Figure 8 and Figure 9 present the winds frequencies distribution from Weibull density of probability at monthly and annual scale during convective diurnal cycle.

The frequency distribution of occurrence of wind speeds on our site reached different peaks depending on the altitude (10 to 60 m) and the months. The most frequent wind speeds on the site at 10 m vary from 2.5 ± 0.56 $m.s^{-1}$ in December to 4.3 $m.s^{-1}$ ± 0.24 in July. The occurence frequencies range from 0.135 (July-August) to 0.18 (December). At 60 m, these frequencies vary from 0.1 in August to 0.137 in November and the most frequent wind speeds from 4.1 ± 0.93 $m.s^{-1}$ (November) to 7 ± 0.24 $m.s^{-1}$ (August). As a function of altitude, we can observe a decrease of the proportion of the most frequent wind speeds, from 0.18 to 0.137 for the least windy months and from 0.135 to 0.1 for the windiest months. Wind speeds more than 10 $m.s^{-1}$ have an occurence frequency between 0.01 in December and 0.04 in July at 10 m. At 60 m, frequencies are higher and range from 0.046 in November-December to 0.09 in July-August. On Figure 9 the annual distribution is presented. The most frequent annual average speed is 3.5 ± 0.40 $m.s^{-1}$ at 10 m during the diurnal cycle with an occurrence frequency of 0.157. This speed reaches the value of 5.4 ± 0.58 $m.s^{-1}$ with a frequency of 0.118 to 60 m of the ground.

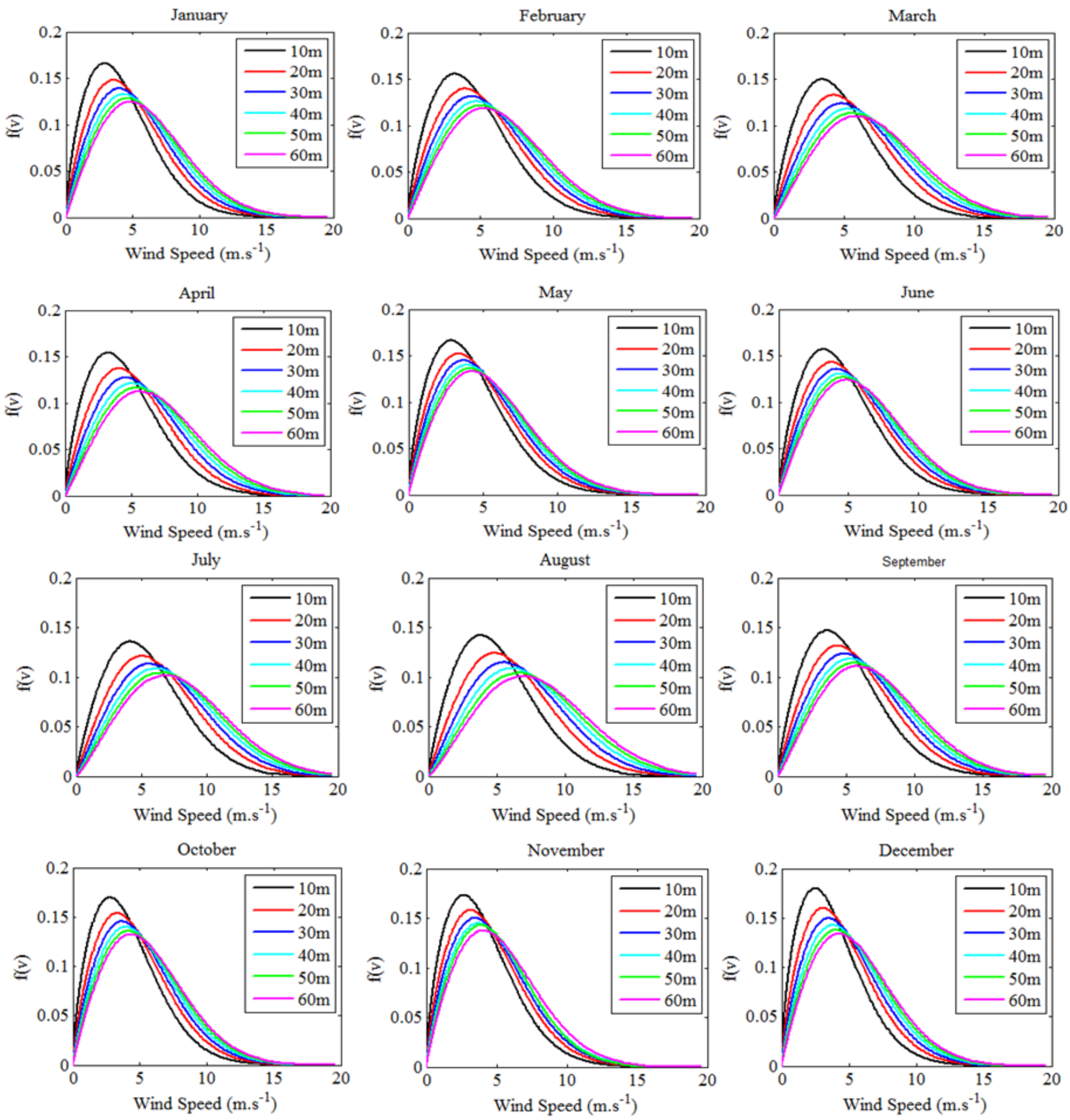

Figure 8. Monthly frequency distribution of wind speeds from Weibull model (2011-2014)

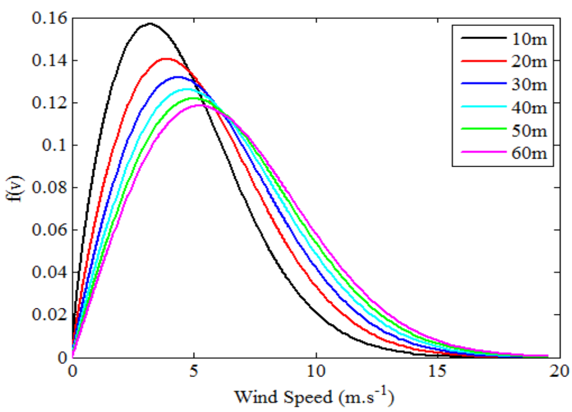

Figure 9. Annual frequency distribution of wind speeds from Weibull model (2011-2014)

These results have been compared with those obtained at the coastal sites of Kribi, Limbe, Douala in Cameroon and some sites in Ghana. We noticed therefore that in Kribi's most probable wind speed was evaluated to 2.42 $m.s^{-1}$, 2.27 $m.s^{-1}$ for Limbe and 1.67 $m.s^{-1}$ for Douala at 10 m above the ground [63]. The most frequent wind speed expected at coastal sites of Adafoah, Anloga, Aplaku, Mankoadze, Oshiyie and Warabeba in Ghana are respectively evaluated to 4.23 $m.s^{-1}$, 3.59 $m.s^{-1}$, 4.34 $m.s^{-1}$, 3.88 $m.s^{-1}$, 3.39 $m.s^{-1}$ and 3.07 $m.s^{-1}$ at 10 m [29]. These values observed on the coastal sites of Ghana are close to those obtained on the coast of Benin. As for Cameroon coastal sites, they are lower.

3.4. Wind Speeds Carrying the Maximum Energy

Figure 10 presents the wind speed giving the maximum energy.

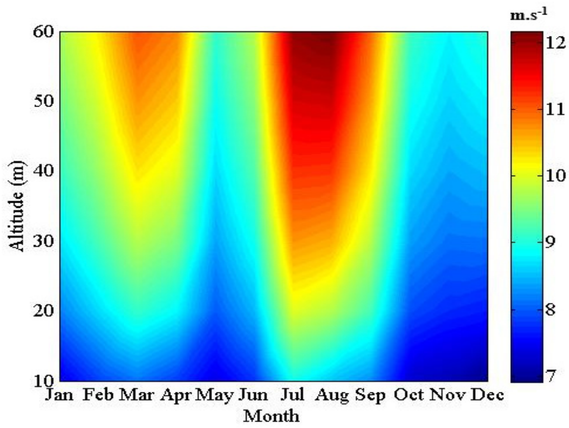

Figure 10. Variation of the wind speed giving the maximum energy as a function of the altitude (2011-2014)

On Figure 10, the wind speeds giving the maximum energy range from 6.91 ± 0.56 $m.s^{-1}$ in December to 8.93 ± 0.24 $m.s^{-1}$ in July at 10 m. At 60 m they are between 8.81 ± 0.93 $m.s^{-1}$ in November and 12.20 ± 0.24 $m.s^{-1}$ in August. Between 10 m to 60m, 26% of these winds are ranged between 10 $m.s^{-1}$ and 12.5 $m.s^{-1}$, 57% between 8 $m.s^{-1}$ and 10 $m.s^{-1}$ and 17% vary from 6.5 $m.s^{-1}$ to 8 $m.s^{-1}$. The majority of winds that give the maximum energy is therefore between 8 and 10 ms^{-1} on the site. Considering the results obtained in section 3.3., these wind speeds are not therefore the most frequent on the site but those which carry the greatest amount of energy.

Referring to the studies of [63], the speeds carrying the maximum of energy were evaluated to 3.35 $m.s^{-1}$ at Kribi's, 3.03 $m.s^{-1}$ at Limbe and 2.0 $m.s^{-1}$ at Douala at 10 m. On the coastal sites of Adafoah, Anloga, Aplaku, Mankoadze, Oshiyie and Warabeba in Ghana, they are respectively estimated at 8.46 $m.s^{-1}$, 7.18 $m.s^{-1}$, 6.81 $m.s^{-1}$, 6.82 $m.s^{-1}$, 5.79 $m.s^{-1}$ and 6.5 $m.s^{-1}$ at 12 m [29]. These values obtained in particular in Ghana are close to those obtained on our site.

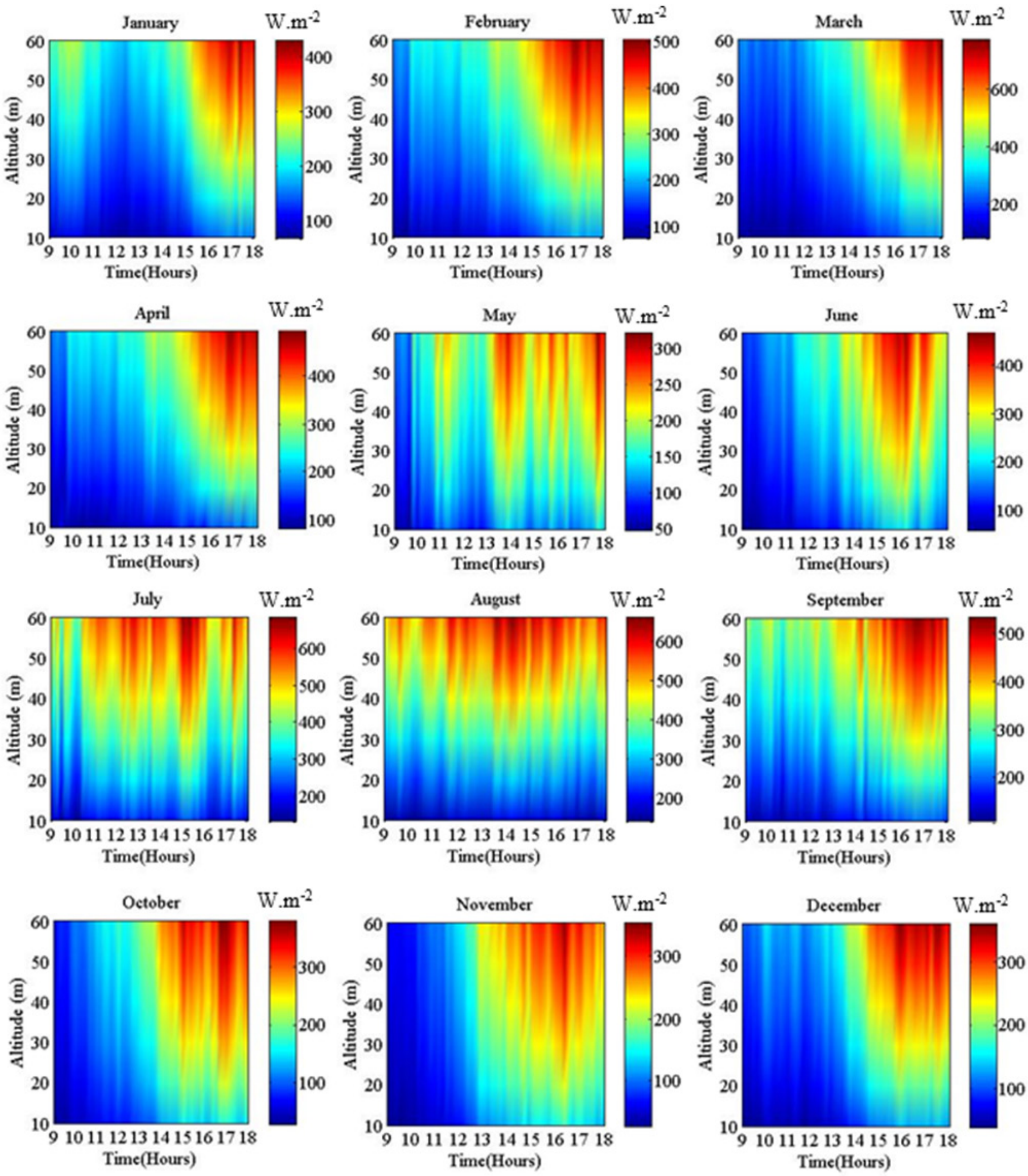

Figure 11. Daily monthly variation of wind energy density from 10 to 60 m at Cotonou Benin (2011-2014)

3.5. Wind Power Density Variation

The variations of wind power density obtained during the convective diurnal cycle at monthly scale are presented in Figure 11.

During the months of February, March, April, June, September to December, we recorded the highiest values of wind potential from 13:00 UTC to 18:00 UTC. These values can reach 770 $W.m^{-2}$ at 17:50 UTC (60 m in altitude) and 271.25 $W.m^{-2}$ at 10 m in March. The low densities obtained during the year have been observed in October with a value of 28 $W.m^{-2}$ (09:00 UTC) at 10 m and of 57.40 $W.m^{-2}$ in November at 60 m (09:00 UTC). In January from 09:00 UTC to 10:00 UTC and 14:30 UTC to 18:00 UTC the wind energy production during the convective diurnal cycle is important than the others period of the day. At 60 m the peak (430 $W.m^{-2}$) of energy in this month has been recorded at 17:20 UTC and the lower (171 $W.m^{-2}$) at 12:20 UTC. The minima of energy at 10 m are evaluated to 67.31 $W.m^{-2}$ and the maxima to 169 $W.m^{-2}$. In May, we noticed a high variability of wind power from 09:40 UTC to 18:00 UTC with a peak (321 $W.m^{-2}$) obtained around 17:40 UTC at 60 m. The low values were obtained between 09:00 UTC and 09:40 UTC varying from 48.27 $W.m^{-2}$ (10 m) to 124 $W.m^{-2}$ (60 m). During the months of July to August, the wind potential varies very little and remains high. The maxima values (respectively of 682 $W.m^{-2}$, 659 $W.m^{-2}$) have been observed around 15:30 UTC in July and at 14:10 UTC in August at 60 m. The low values reached at 10 m during these two months are respectively estimated to 130.71 $W.m^{-2}$ (09:30 UTC) and 140.54 $W.m^{-2}$ (11:20 UTC).

The maximal wind power density for the most of the months is therefore recorded after 13:00 UTC. The lower level is observed between 09:00 UTC and 12:30 UTC except May, July, August, September where we recorded some high values. On Figure 12 the average monthly density of wind energy are presented during the convective diurnal cycle.

The wind power density in the coastal region of Cotonou, Benin varies in function of month and is strongly influenced by the different seasons of the year. The graphs of Figure 12 show two peaks obtained during the year. The first in March and the second in July or in August depending on the altitude. Figure 12 shows an increase in wind energy from January to March, followed by a decrease from April to May. From June to July, we observe again an increase of energy and from August to December a decrease. These different variations have been observed between 10 m and 30 m altitude. From 40 m to 60, we noted a slight increase of energy from November to December and the second energy peak of the year is obtained in August from 50 to 60 m. The period of the year in which wind energy production is the highest is therefore in March and from July to September. The period of the lowest production, is in May, and from October to December on our study site. The quantity of energy recoverable in terms of the power density at 10 m from the ground varies from 87 $W.m^{-2}$ obtained in December to 200 $W.m^{-2}$ in July. At 60 m the energy density varies from 206 $W.m^{-2}$ in November to 559 $W.m^{-2}$ in August. The cumulative density of wind power obtained at 10 m above the ground during the great dry season (December to March) is estimated to 475.43 $W.m^{-2}$. During the great rainy season (April to July), values are estimated to 561.43 $W.m^{-2}$. From August to September, the period of the short dry season, the recoverable potential reaches the value of 324.83 $W.m^{-2}$ and during the short rainy season (October-November), it is estimated to 203.54 $W.m^{-2}$. These different cumulation have been evaluated respectively to (685.94 Wm^{-2}, 786.89 Wm^{-2}, 490.24 $W.m^{-2}$, 272.44 $W.m^{-2}$) at 20 m, (852.89 $W.m^{-2}$, 959.40 $W.m^{-2}$, 626.25 $W.m^{-2}$, 323.92 Wm^{-2}) at 30 m, (996.78 $W.m^{-2}$, 1106 $W.m^{-2}$, 746.30 $W.m^{-2}$, 366.62 $W.m^{-2}$) at 40 m, (1125 $W.m^{-2}$, 1235 $W.m^{-2}$, 855.82 $W.m^{-2}$, 403.79 $W.m^{-2}$) at 50 m and (1243 Wm^{-2}, 1353 $W.m^{-2}$, 957.67 $W.m^{-2}$, 437.08 $W.m^{-2}$) at 60 m. More energy is therefore produced during the great rainy season. From 10 m to 60 m above the ground, the energy increases by 61.78% during the great dry season, 58.53 % during the great rainy season, 66.14 % during the short dry season and 53.54 % during the short rainy season. The average annual quantity of power density is estimated at 131 $W.m^{-2}$ at 10 m and 332.67 $W.m^{-2}$ at 60 m, a growth rate of 60.6 %. At 20 m the annual power density is 186.29 $W.m^{-2}$, of 230.20 $W.m^{-2}$ (30 m), of 267.96 $W.m^{-2}$ (40 m) and at 301.74 $W.m^{-2}$ (50 m).

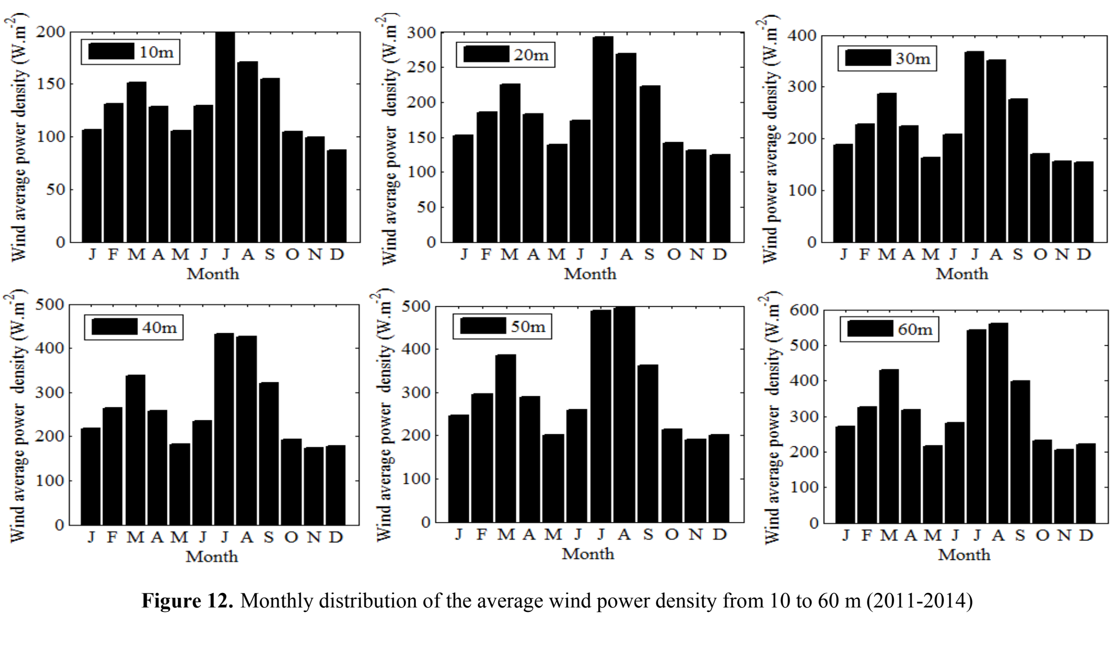

Figure 12. Monthly distribution of the average wind power density from 10 to 60 m (2011-2014)

These different results obtained have been compared to the studies of [27,29,32,35,36,37,41] in West Africa. It ensues that on the coastal areas of West Africa particulary in Nigeria, Togo, Ghana, Senegal and Benin, the wind energy potential is more important at some places, than others. It is the case of Adafoah coastal site in Ghana whose annual wind potential is evaluated at 174.86 W.m^{-1} at 12 m. On Sine Moussa coastal site in Senegal, the power density is estimated to 143 W.m^{-2} (12 m) in day time. These values are greater than the one obtained by this study (130.43 W.m^{-2}). On the coastal site of Ikeja in Nigeria the lowest and highest values of power density were respectively recorded in the months of November and August with values of 19.6 and 359.3 W.m^{-2} at 10 m. This site therefore present some similar characteristics with our site where, in July-August the power density reaches its maximum values during the year and in November-December, its lowest values. However the power density obtained in Ikeja is higher than the one obtained on our site. As for the coastal sites of Accra, Anloga, Aplaku, Mankoadze, Oshiyie, Warabeba in Ghana (day and night wind potential) at 10 m, the wind energy potential is respectively equal to 97.75 W.m^{-2}, 107.19 W.m^{-2}, 105.19 W.m^{-2}, 98.04 W.m^{-2}, 61.10 W.m^{-2}, and 78.46 W.m^{-2}. On coastal sites of Calabar, Uyo, and Warri in Nigeria (day and night wind potential), it is respectively estimated at 21.4 W.m^{-2}, 48.9 W.m^{-2}, and 23.6 W.m^{-2} at 10 m. In Senegal, on coastal sites of Kayar, Potou, Gandon, Botla, Dara Andal, Nguebeul, Sakhor in Senegal (day wind potential) the annual wind energy potential is evaluated respectively to 99.64 W.m^{-2}, 145.30 W.m^{-2}, 103.14 W.m^{-2} at 20 m and to 128.59 W.m^{-2}, 107.74 W.m^{-2}, 106.61 W.m^{-2} and 117.53 W.m^{-2} at 10 m. In Lome (Togo), the annual daily wind energy potential is respectively evaluated to 64.52 W.m^{-2} at 10 m. At 30 m and 50 m in Lomé and Accra the wind potential is respectively equal to 103.08 W.m^{-2}, 130.41 W.m^{-2} in Lomé and to 147.5 W.m^{-2}, 185 W.m^{-2} in Accra. These different values are lower than the values obtained in this study, in particular and those obtained in Lomé, Accra and Nigeria. This could be due to the measure time scale of wind data used to perform these different studies on the wind power energy. The extrapolation models used by some authors to determine wind profile at the hub height of the wind turbines could underestimate or overestimate the wind energy power. The period of day time chosen (day and night) by some authors to carry out their study could also explain these values. On the site of Cotonou, it is in the period of 09:00 UTC with 18:00 UTC that the study was used done.

To characterize the sites which are suitable candidates to host the wind power plants or large-scale electric wind application, [65] estimated that on these sites, the wind power density must be above 400 W.m^{-2} or even reach 800 W.m^{-2} at a height of 50 m with wind speed more than 7 m.s^{-1}. In the studies of [65] reported by [27], the authors think that the stations can be classified based on their wind power as shown in the Table 2.

Thus from this Table, areas designated as class 1 are generally not suitable for wind turbine applications while class 2 areas are marginal. Areas which can be classified as class 3 or greater are suitable for most wind turbine applications [27,66]. From these considerations and taking into account the results presented at the Figure 4 and Figure 5 and Figure 11 and Figure 12, the coastal area of Cotonou could be suitable for the installation of small and large wind turbines in order to supply in power energy.

Table 2. Classes of wind power density at 10 m and hub heights [27]

Wind Power Class	10 m		Hub-heights (m)	
	Wind Power density (W. m^{-2})	Speed (m.s^{-1})	Wind Power density (W. m^{-2})	Speed (m.s^{-1})
1	0-100	0-4.4	0-200	0-5.6
2	100-150	4.4-5.1	200-300	5.6-6.4
3	150-200	5.1-5.6	300-400	6.4-7
4	200-250	5.6-6	400-500	7-7.5
5	250-300	6-6.4	500-600	7.5-8
6	300-400	6.4-7.0	600-800	8-8.8
7	400-1000	7.0-9.4	800-2000	8.8-11.9
8	$\succ$ 1000	$\succ$ 9.4	$\succ$ 2000	$\succ$ 11.9

4. Conclusion

The variability of wind energy potential between 10 and 60 m in the south of Benin has been studied during the convective diurnal cycle. The following conclusions can be drawn:

1. The month of July is the windiest during the year and the average wind speed is evaluated at 5.43 ± 0.24 m.s^{-1} and in December, the lowest value is of 3.83 ± 0.56 m.s^{-1} at 10 m. At 60 m in August we recorded the highiest value of the average wind speed (8.05 ± 0.24 m.s^{-1}) and in November, the low value (5.32 ± 0.93 m.s^{-1}). The annual average wind speed varies from 3.9 m.s^{-1} to 7.1 m.s^{-1} during the convective diurnal cycle between 10 and 60 m.
2. the annual mean parameters k and c of Weibull were evaluated respectively from 1.78 to 2.05 and from 5 to 7.4 m.s^{-1}. The most frequent wind speeds on the study site are between 2.5 ± 0.56 m.s^{-1} in December to 7 ± 0.24 m.s^{-1} in August from 10 to 60 m. The average wind speeds giving the maximum of energy varies from 6.91 ± 0.56 m.s^{-1} in December at 10 m to 12.20 ± 0.24 m.s^{-1} in August at 60 m.
3. Finally, the wind energy potential evaluated reveals that the largest quantities of energy are generally collected between 13:00 UTC and 18:00 UTC. During the months of March, July and August the daily energy peaks are observed between 14:00 UTC and 18:00 UTC of the order of 250 to 258 W.m^{-2} at 10 m and of 650 to 770 W.m^{-2} at 60 m. The monthly average of the energy potential for these months is respectively evaluated to (429 W.m^{-2}; 542.14 W.m^{-2} and 559.96 W.m^{-2}) at 60 m and to (151.22 W.m^{-2}; 200 W.m^{-2} and 170.31 W.m^{-2}) at 10 m. The lowest quantities of wind power energy are observed at 10 m in December (86.81 W.m^{-2}) and in November (205 W.m^{-2}) at 60 m. The annual energy potential has been estimated at 130.43 W.m^{-2} (10 m) and 332.67 W.m^{-2} (60 m).

Our study site is therefore suitable to shelter electrical energy production installations, from wind turbines.

Specifically, wind turbines with a starting speed of between 2 and 3 m.s^{-1} will be valuable. This production can therefore provide energy autonomy to populations, particularly in rural areas for pumping water, heating water and electricity production. For a complete estimate of the wind energy resource, we will look in the future at the variability of the wind power density during the nocturnal cycle of the wind.

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Statement of Competing Interests

The authors declare no conflict of interest.

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