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► **To cite this version:**

S. Madougou, F. Saïd, Bernard Campistron, C.F. Kebe. Economic study of the wind energy potential in Sahel. *Journal of Energy and Power Engineering*, 2013, 7, pp.47-51. 10.17265/1934-8975/2013.01.006 . hal-00766790

**HAL Id: hal-00766790**

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Submitted on 12 Mar 2021

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# Economic Study of the Wind Energy Potential in Sahel

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Received: August 06, 2012 / Accepted: November 08, 2012 / Published: January 31, 2013.

**Abstract:** The wind pattern in Sahel is marked by a strong diurnal cycle as well as a strong seasonal cycle. The low level jet is blowing above the near-surface layer during nighttime and is decoupled from the surface. Nowadays, some studies showed the possibility to use the sub-jet wind at levels higher than 90 m as a source of energy in this area. In the present work, the wind turbines, with hub heights situated at 150 m and blade extremities at  $150 \pm 60$  m, were used to make an economic study of wind energy potential in Sahel. Thus, monthly wind power was determined by two methods. The first involved the wind distributions directly observed. The second was based on the Weibull distributions which were fitted to the data. Day and night were compared. Results showed that this jet was an attractive source of energy provided if huge-capacity energy storage was used. So, the energy stored at night could be restored during the daytime, when the demand is highest. An economic study was done to estimate the number of wind turbines needed to satisfy the Niamey demand. The cost was found reasonably cheap relative to that of other renewable energy sources.

**Key words:** Wind energy, wind turbine, nocturnal low level jet, dry season, monsoon.

## 1. Introduction

In areas which are not easily reachable for long-term observations, statistical models are very often used to describe wind speed regimes and forecast wind power potential in a region or a country [1]. According to the literature relating to wind energy, several models of probability density function are used to describe the characteristics of wind speed.

Among these, for example, it can cite: the isotropic Gaussian model from Refs. [2-4]; the anisotropic Gaussian model from Ref. [5]; the two-parameter Weibull probability distribution from Refs. [6-8]; the Beta probability density function of three parameters (two shape parameters and one scale parameter) used by Lavagnini et al. [9].

This list can be added the three-parameter Gamma distribution proposed by Auwera et al. [10] for estimation of mean wind power densities, the

three-parameter variant of the Weibull distribution (shape parameter, scale parameter and location parameter) proposed by Stewart et al. [11], the inverse Gaussian probability density function of two parameters suggested by Bardsley [12] as an alternative to the three-parameter Weibull distribution.

However, the distribution most widely adopted, in the specialized literature on wind energy studies, is the two-parameter Weibull probability distribution [13-15]. Using a two-parameter Weibull distribution, Edgar and O'Brien [16] studied the probability distribution of wind speed data over the world's oceans. They established the parameters of the distribution following a linearized least-squares approach and presented the seasonal and latitudinal variations of Weibull parameters using Hovmöller diagrams. Mathew et al. [17] presented an analysis of wind regimes for energy estimation in India. In that paper, the authors discussed the use of the Rayleigh distribution, which is a special case of the Weibull distribution and concluded that the characteristics of the wind turbine, in terms of cut-in

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and cut-out velocities, had considerable influence on the monthly energy output from the wind turbine. Weisser [18] showed the importance of incorporating the variation in wind energy potential during the diurnal cycle. He noted that wind energy assessment based on the Weibull distribution using daily/seasonal wind speeds fails to acknowledge that wind speed probabilities can vary significantly during the day and the night. Celik [19] compared the wind potential of the southern region of Turkey based on the Weibull and Rayleigh models. Also, Carta et al. [20] analyzed the complexity of the estimation and the fit to the wind speed experimental data according to the estimation method chosen. The authors concluded that the Weibull probability density function presented a series of advantages with respect to the other probability density functions analyzed. However, they also showed that the Weibull probability density function could not represent all the wind regimes encountered in natural situations, such as those with high percentages of null wind speeds, bimodal distributions, etc..

Nowadays, with the emergence of the new 2 MW to 6 MW wind turbines that can reach 100 m to 200 m height, the future of wind energy will be in offshore installations and low-level jet wind farms inland, because these locations have more wind potential than the continental areas (for the former) or more wind than at a few meters above the ground (for the latter).

The data used in this study come from two UHF (ultra high frequency) wind profiler radars installed at the airports of Bamako (12°32' N, 7°57' W, 380 m asl, south west Mali) in 2005 and of Niamey (13°29' N, 2°10' E, 227 m asl, south west Niger) in 2006, both situated in the Sahel band and roughly 100 km apart in latitude. The radars provided a data set of the low layer wind characteristics with a fine time resolution and also good statistics of the wind at a constant level. Ref. [1] shows that the wind patterns of the observed area are highly variable, on both the seasonal and diurnal scales. The prevailing directions are the north-eastern Harmattan during the dry season and the south-western

monsoon during the wet season. At low levels, the dominating wind is due to the NLLJ (nocturnal low level jet). This jet produces by night relatively strong values of wind speed, which can reach  $10 \text{ m}\cdot\text{s}^{-1}$  at 150 m whereas the wind in the first tens of meters above the surface remains weak. As the wind intensity can decrease to rather low values during the daytime, it is necessary to perform an accurate analysis of the wind potential, in order to check whether the wind pattern is favorable or not for the generation of electricity.

Here, the wind measurements are estimated at the 150 m and 210 m profiler gate levels in Niamey, 147 m and 185 m in Bamako. 150 m was chosen on one hand because it is the level of the first gate of the profilers, and on a second hand because the wind is too weak at levels lower than 90 m [21] to be used for wind turbines. Therefore, the use of wind turbines with a hub height of 150 m is considered. Few wind turbines of that height are presently available, but some prototypes exist with a hub level as high as 200 m. Otherwise, civil engineering will be required to raise the turbine hubs.

Two criteria are considered to select the wind turbines: (1) the hub height and length of the blades; (2) the characteristic speeds (cut-in, rated and cut-out speeds) of the turbines. Two turbines, among others, were found to fill the first criterium (the second criterium will be discussed in Section 4). The hub height  $\pm$  blade length proposed by Vestas (model V112) is  $119 \pm 63 \text{ m}$  and by Enercon (model E-82),  $138 \pm 41 \text{ m}$ . So instead of 119 m and 138 m, both rotors are installed at 150 m (with the help of civil engineering) which makes rotor blades ranges between 87 m and 213 m for Vestas and 110 m and 190 m for Enercon E-82. This is the reason why the wind potential is studied here at the three levels: 90 m, 150 m and 210 m, which roughly covers the range of the Vestas turbine and includes the range of the Enercon one, while allowing reaching the minimum level for the jet to blow.

Section 2 presents a brief theoretical background of wind power analysis. Section 3 describes the monthly wind patterns and makes the distinction between nights

and days. Wind speed distributions are shown in Section 4 and compared to Weibull probability densities. Wind power is calculated in Section 5, an economic study is presented in Section 6 and finally section 7 concludes this paper.

## 2. Theoretical Background

### 2.1 Weibull Distribution

The Weibull probability distribution is the most widespread model used to describe wind speed frequency distributions. It is a probability density function defined by two parameters: a scale parameter  $c$  ( $\text{m}\cdot\text{s}^{-1}$ ) and a dimensionless shape parameter  $k$ . Weisser [18] comments that “the scale parameter,  $c$ , indicates how ‘windy’ a wind location under consideration is, whereas the shape parameter,  $k$ , indicates how peaked the wind distribution is”.

The Weibull distribution is defined by its probability density function  $f(V)$  and its cumulative function  $F(V)$  is given by:

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

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

where,  $V$  ( $\text{m}\cdot\text{s}^{-1}$ ) is the horizontal wind speed. One advantage of the Weibull distribution is that it requires only two parameters whereas the bi-variate normal distribution requires five. In a large number of cases, this distribution provides good fits to observed distributions.

When the shape parameter,  $k = 1$ , it gives the well known exponential law. When  $k = 2$ , the distribution is referred to as a Rayleigh distribution [15, 22-24], and the probability density function  $f_R(V)$  is then given by:

$$f_R(V) = 2\frac{V}{c^2} \exp\left[-\left(\frac{V}{c}\right)^2\right] \quad (3)$$

The advantage of the Rayleigh distribution is that it allows convenient simplifications while still providing reasonable fits with observed wind velocities, since

most distributions are close to a Gaussian.

The main limitation of the Weibull density function is that it does not accurately represent the probabilities of very low wind. To cope with this difficulty, Takle et al. [25] and Persaud et al. [26] proposed to use the hybrid Weibull distribution for wind speed distributions with non-zero probability of null wind speeds (probability of calm winds  $> 15\%$ ). In this case, the probability density function  $f_{hw}(V)$  is given by:

$$f_{hw}(V) = (1 - F_0)\left(\frac{k}{c}\right)\left(\frac{V}{c}\right)^{k-1} \exp\left[-\left(\frac{V}{c}\right)^k\right] \quad (4)$$

$F_0$  is the frequency of null wind speed given by:  $F_0 = f_{V=0}$ .

### 2.2 Weibull Parameters Estimation

Several methods are used to estimate the two Weibull parameters according to the available wind speed data [14, 18, 27, 28]. Among them, the most used are: (1) the mean wind speed and standard deviation method; (2) the least-squares fit to observed distribution method.

#### (a) Mean wind speed and standard deviation

This method is used when the wind distribution is not available but the mean wind speed  $\bar{V}$  and the standard deviation  $\sigma$  are provided. In this case, the coefficients  $k$  and  $c$  can be derived from [14, 18]:

$$k = \left(\frac{\sigma}{\bar{V}}\right)^{-1.086} \quad (k \geq 1) \quad (5)$$

$$c = \frac{\bar{V}}{\Gamma\left(1 + \frac{1}{k}\right)} \quad (6)$$

where,  $\bar{V} = \frac{1}{n} \sum_{i=1}^n V_i$  and  $\sigma^2 = \frac{1}{n-1} \sum_{i=1}^n (V_i - \bar{V})^2$ .

$\Gamma(x)$  is the usual Gamma function defined by:

$$\Gamma(x) = \int_0^{\infty} \exp(-t)t^{x-1} dt \quad \text{and} \quad \Gamma(1+x) = x\Gamma(x).$$

#### (b) Least-squares fit to observed distribution

This method is often used to determine the two parameters by partitioning the Weibull probability density function  $f(V)$  into frequencies of occurrence

$f_1, f_2, \dots, f_n$  and cumulative frequencies:  $p_1 = f_1, p_2 = f_1 + f_2, \dots, p_n = p_{n-1} + f_n$ . The logarithmic forms give:

$$x_i = \ln(V_i) \quad (7)$$

$$y_i = \ln[-\ln(1 - p_i)] \quad (8)$$

Then Eq. (2) transforms to the linear form  $y_i = ax_i + b$ . Applying a least-squares fit to the values obtained provides  $a$  and  $b$  and the two parameters  $k$  and  $c$ , using [14, 28, 29]:

$$k = a \quad (9)$$

$$c = \exp\left(-\frac{b}{a}\right) \quad (10)$$

### 2.3 Wind Power

When the wind blows on a site, the power available in the wind stream per unit area is given by [30]:

$$P(V) = \frac{1}{2} \rho V^3 \quad (11)$$

where  $\rho$  is the air density and  $V$  is the wind speed.

The wind power density per unit area based on the observed probability density distribution  $f(V)$  is:

$$P(V) = \frac{1}{2} \rho \int_0^{\infty} V^3 f(V) dV \quad (12)$$

The wind power density (per unit area) of the site, based on the Weibull probability density function  $f(V)$  is given by:

$$P_w = \frac{1}{2} \rho c^3 \Gamma\left(1 + \frac{3}{k}\right) \quad (13)$$

Table 1 gives the wind power densities for the hybrid of Weibull or Rayleigh distributions.

When the wind turbine is defined by its cut-in speed ( $V_i$ ), rated wind speed ( $V_r$ ) and cut-out speed ( $V_c$ ), the wind power output from the wind turbine,  $P_T$  can be determined from its wind turbine performance curve by summing the following terms:

$$P_T = \begin{cases} 0 & \text{for } V < V_i \\ \frac{1}{2} \rho A \int_{V_i}^{V_r} V^3 & \text{for } V_i < V < V_r \\ P_r \int_{V_r}^{V_c} f(V) dV & \text{for } V_r < V < V_c \\ 0 & \text{for } V > V_c \end{cases} \quad (14)$$

where  $P_r$  is the rated wind power expressed by:

$$P_r = \frac{1}{2} \rho A V_r^3 . A \text{ is the area swept by the rotor. The energy is obtained by multiplying the wind power by the running time } t: E_T = P_T \cdot t.$$

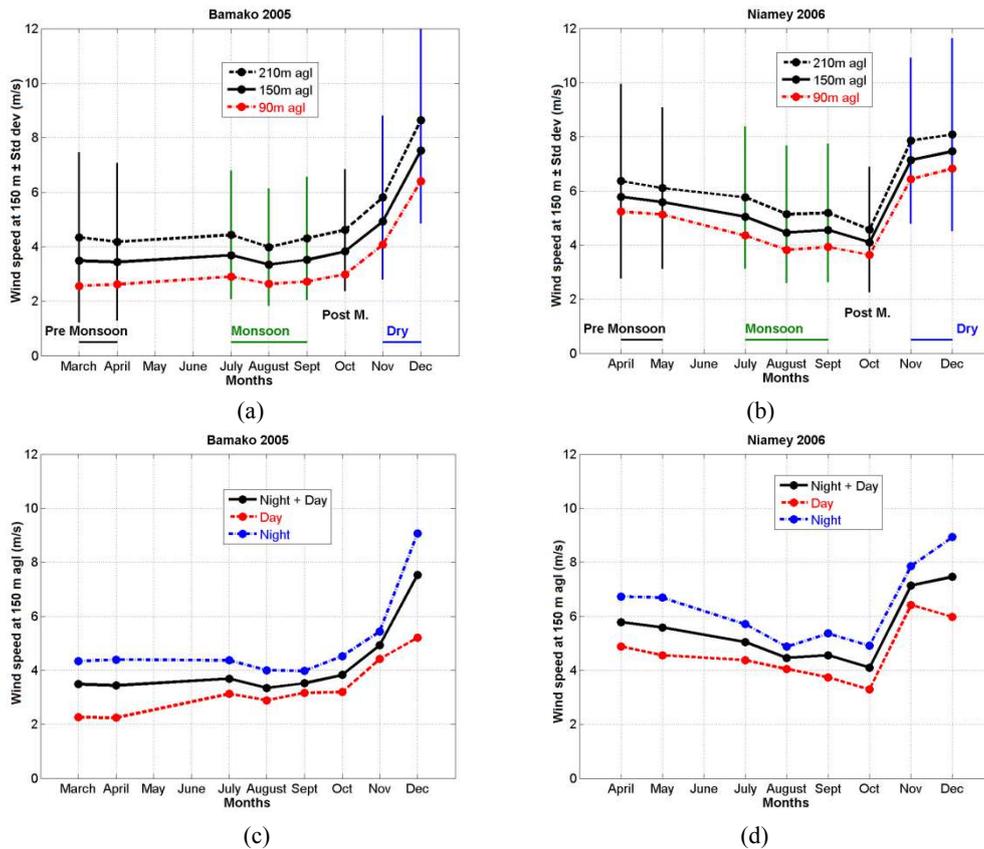
**Table 1 Wind power density for Weibull, hybrid of Weibull and Rayleigh distributions.**

Distributions	Wind power density
Weibull	$\frac{1}{2} \rho c^3 \Gamma\left(1 + \frac{3}{k}\right)$
Hybrid of Weibull	$\frac{1}{2} \rho (1 - F_0) c^3 \Gamma\left(1 + \frac{3}{k}\right)$
Rayleigh	$0.66 \rho c^3$

### 3. Monthly Patterns of the Wind Speed

The data presented in Ref. [1] focused on the four characteristic seasons: the dry season (November to December), the pre-monsoon (March-April in Bamako, April-May in Niamey), the monsoon (July to September) and the post-monsoon (October). Both transition periods (pre- and post-monsoon) experienced, during some days, the monsoon wind during the night and the Harmattan wind during the day. The wind velocity was rather weak during the day, all over the year. The NLLJ reached its strongest values during the dry season and peaked at lower heights than during the other periods, which produced large wind velocity gradients near the surface. Here hourly observations, from the wind profilers at 150 m agl, are used. Then, to get an idea of the wind properties at the turbine blades extremities, an investigation at the wind at 210 m and 90 m is made, considering 120 m long blades. The 210 m-velocity was directly obtained from the first two gates at Niamey, or extrapolated in Bamako. 90 m wind values were also extrapolated. A linear extrapolation is used that has revealed to match in the data (Ref. [1]): NLLJ profiles are linear in the sub-jet layer from a few tens of meters above the surface to some distance from the jet nose that peaks most of the time over 200 m agl. Daytime winds are relatively weak, which also allows a linear extrapolation, provided it is done at the top or outside the surface layer.

Figs. 1a and 1b present the monthly pattern of the wind velocity at 210 m, 150 m and 90 m agl, at Bamako and Niamey. Its variability during the month is also shown with the standard deviation at 150 m.



**Fig. 1** (Top) Monthly wind speed at 210 , 150 and 90 m agl at (a) Bamako in 2005 and (b) Niamey in 2006. The vertical lines join the monthly average  $\pm$  the standard deviation at 150 m. (Bottom) Monthly wind speed at 150 m agl, according to the time of the day at (c) Bamako and (d) Niamey.

At Bamako, the 150 m monthly mean wind speed varies very little from the pre-monsoon to the post-monsoon ( $3\text{--}3.5\text{ m}\cdot\text{s}^{-1}$ ), then begins to increase, reaching  $7.5\text{ m}\cdot\text{s}^{-1}$  during December. At Niamey, it decreases from the pre-monsoon ( $6\text{ m}\cdot\text{s}^{-1}$ ) to the post-monsoon ( $4\text{ m}\cdot\text{s}^{-1}$ ). During the winter period (dry season), the mean wind speed also reaches  $7.5\text{ m}\cdot\text{s}^{-1}$ . Ref. [1] saw that the highest wind speeds are linked to the presence of a strong NLLJ. The monthly standard deviation is lower during the monsoon and post-monsoon periods, which is consistent with less frequent occurrences of the NLLJ during these periods. The wind velocity difference between the 150 m and 210 m or 90 m levels is rather constant for the two locations (around  $1.7\text{ m}\cdot\text{s}^{-1}$  in Bamako and  $1.2\text{ m}\cdot\text{s}^{-1}$  in Niamey). A larger difference has been expected in winter, due to the larger NLLJ gradients, but the 24 h-average hid any discrepancy of that kind.

Figs. 1c and 1d differentiate between night patterns (2000 UTC to 0800 UTC), day patterns (0800 UTC to 2000 UTC) and those of the whole diurnal cycle, at 150 m agl. The monthly mean values of nighttime wind speeds are much higher than those of the daytime and logically above the overall average (whole cycle), whatever the month of the year. This confirms that it is mainly the NLLJ that produces wind. The gap is even greater during the dry season. The differences between nights and days are similar at Bamako and Niamey and vary between  $1\text{ m}\cdot\text{s}^{-1}$  in summer, when the NLLJ is the weaker and  $3\text{ m}\cdot\text{s}^{-1}$  or  $4\text{ m}\cdot\text{s}^{-1}$  in winter.

In order to calculate the wind energy potential, it is necessary to determine the distributions of the wind speeds which are the subject of next section.

#### 4. Wind Speed Distributions

The distributions were calculated with wind intervals

of 1 m·s<sup>-1</sup> and are represented in Figs. 2-5 for the four characteristic seasons with a distinction between nights and days and between the levels. As the Weibull probability distribution is currently the standard for the statistical representation of the climatology of wind

farms, a comparison of observed distributions obtained in this work is made with the corresponding Weibull probability distributions to check the agreement. In this study, when the frequency of calm winds was relatively large (i.e., when the first channel frequency was

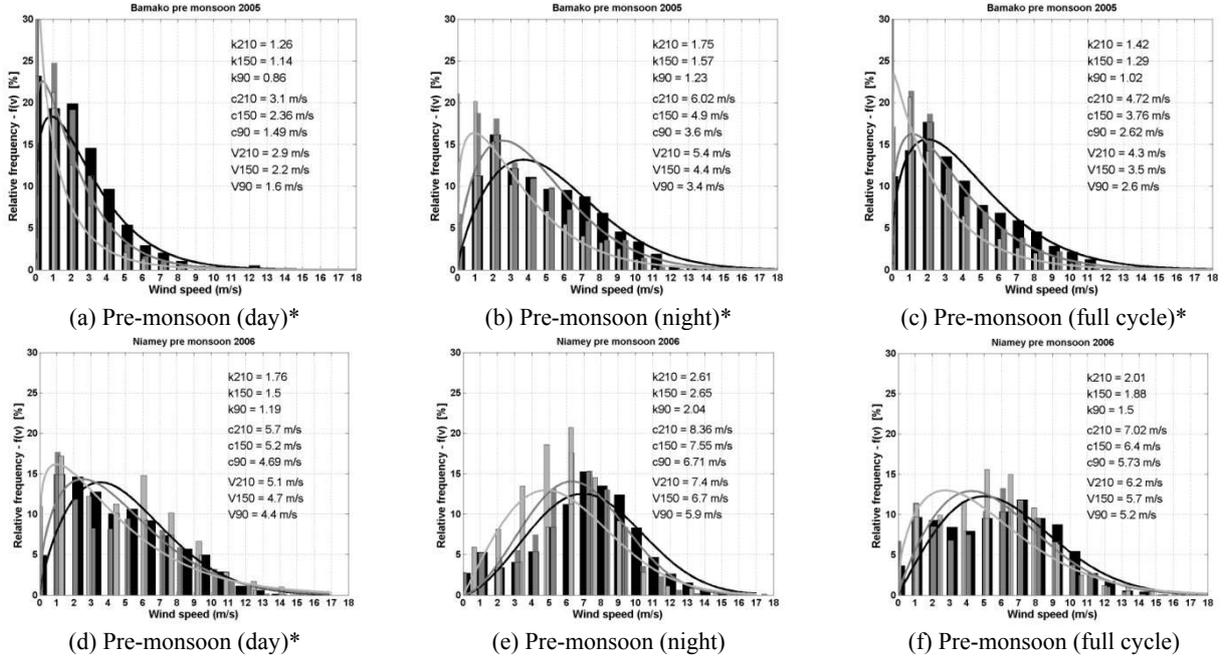


Fig. 2 Observed probability distribution (bins) and Weibull probability distribution (lines) of the wind speed in the pre-monsoon period during day, night and both day and night at (top) Bamako and (bottom) Niamey. \* Weibull hybrid distribution is used for one level at least. Level 210 m agl is in black, 150 m in grey and 90 m in light grey.

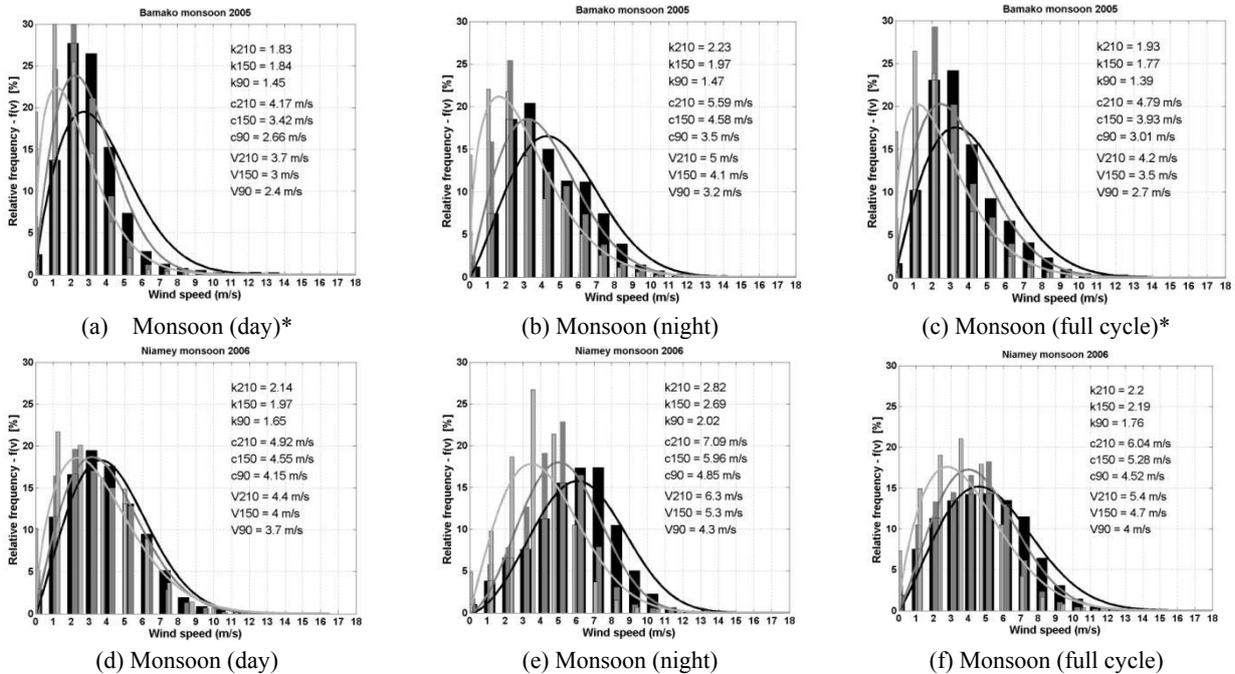


Fig. 3 Same as in Fig. 2 but for the monsoon period (July to September).

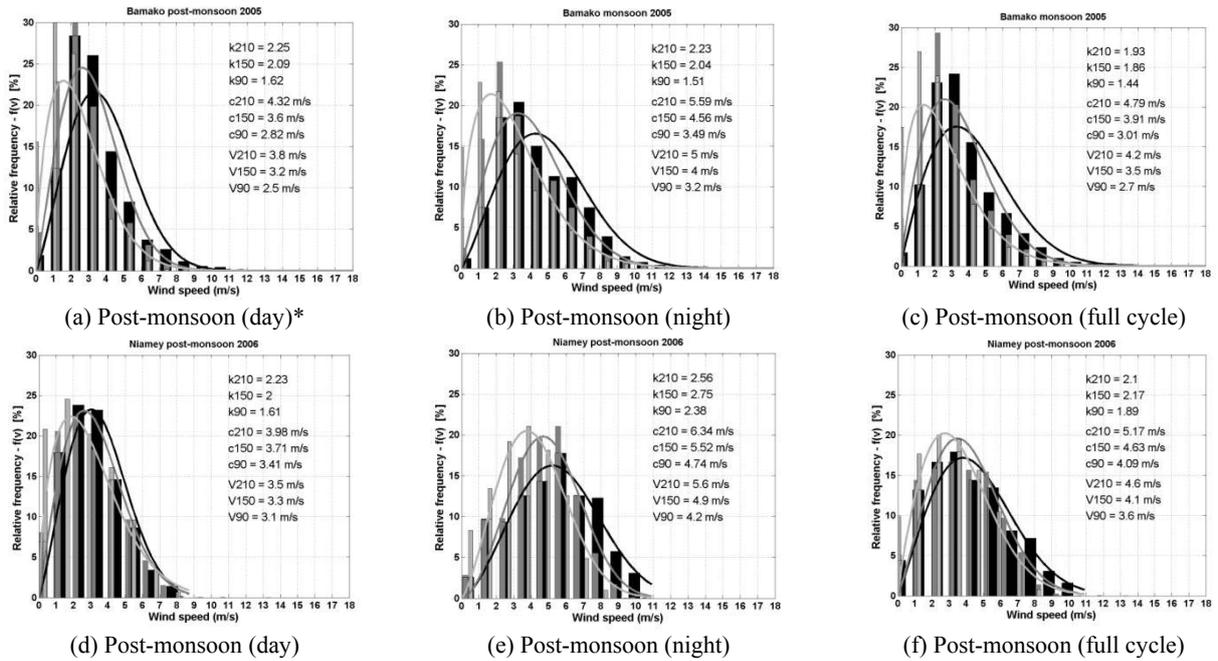


Fig. 4 Same as in Fig. 2 but for the post-monsoon period (October).

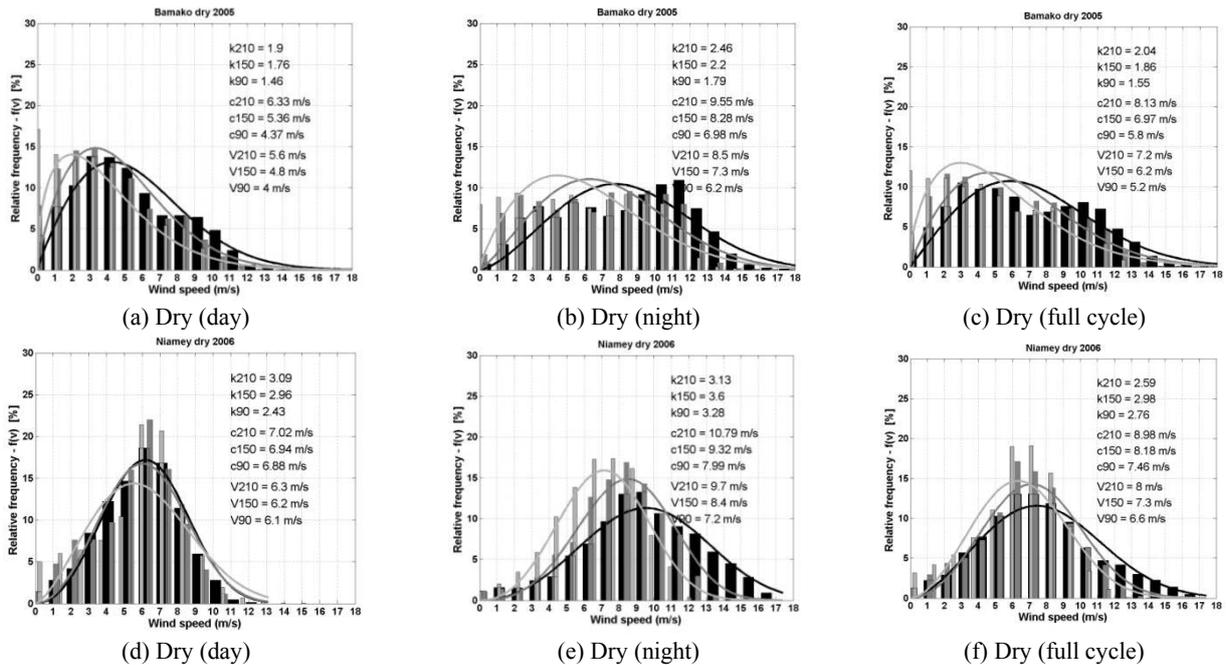


Fig. 5 Same as in Fig. 2 but for the dry period (November-December).

greater than 15%), the hybrid distribution of Weibull is applied. The Weibull parameters  $c$  and  $k$  were estimated by both methods described in Section 2.2. Both provided similar results, but, the first method (mean wind speed and standard deviation method) is finally selected, since it gave  $c$  parameters closer to the mean wind speed values.

Table 2 summarizes the seasonal values of Weibull parameters  $c$  and  $k$  in Bamako and in Niamey at the three different levels. \* indicates that Weibull hybrid distribution is used.

The hybrid distribution of Weibull has applied for the pre-monsoon cases in Bamako (top of Fig. 2), which means that weak winds are rather frequent. Even

**Table 2 Weibull parameters  $k$  and  $c$  obtained during day, night and the whole diurnal cycle at Bamako and Niamey, at 210, 150 and 90 m agl (from top to bottom).**

	Weibull parameters					
	$k$			$c$ (m·s <sup>-1</sup> )		
	Day	Night	Full cycle	Day	Night	Full cycle
<b>Bamako</b>						
	1.26*	1.75	1.42	3.1*	6.0	4.7
Pre-monsoon	1.14*	1.57	1.29*	2.4*	4.9	3.8*
	0.86*	1.23*	1.02*	1.5*	3.6*	2.6*
	1.83	2.23	1.93	4.2	5.6	4.8
Monsoon	1.84	2.04	1.86	3.4	4.6	3.9
	1.45*	1.51	1.44*	2.7*	3.5	3.0*
	2.25	2.50	2.19	4.3	6.2	5.2
Post-monsoon	2.09	2.22	2.01	3.6	5.1	4.3
	1.62	1.65	1.56	2.8	3.9	3.3
	1.90	2.46	2.04	6.3	9.6	8.1
Harmattan	1.76	2.20	1.86	5.4	8.3	7.0
	1.46*	1.79	1.55	4.4*	7.0	5.8
<b>Niamey</b>						
	1.76	2.61	2.01	5.7	8.4	7.0
Pre-monsoon	1.50	2.65	1.88	5.2	7.6	6.4
	1.19	2.04	1.50	4.7	6.7	5.7
	2.14	2.82	2.20	5.0	7.1	6.0
Monsoon	1.97	2.69	2.19	4.6	6.0	5.3
	1.65	2.02	1.76	4.2	4.9	4.6
	2.23	2.56	2.10	4.0	6.3	5.2
Post-monsoon	2.00	2.75	2.17	3.7	5.5	4.6
	1.61	2.38	1.89	3.4	4.7	4.1
	3.09	3.13	2.59	7.0	10.8	9.0
Harmattan	2.96	3.60	2.98	6.9	9.3	8.2
	2.43	3.28	2.76	6.9	8.0	7.5

\*indicates that Weibull hybrid distribution is used.

if the percentage of very weak winds is not always larger than 15%, most histograms during this period are close to the exponential law ( $k$  coefficients smaller or close to 1 in Table 2). To try to understand this shift of the distributions towards low wind values, the data, recovery rate in Bamako at the 150 m UHF gate level, are used. The data recovery rate is defined as the number of valid data records collected, versus that possible over the selected period. It was only 65% during the pre-monsoon period for respectively 82%, 85% and 65 % for the monsoon, post-monsoon and dry periods. 65% nonetheless means 22,838 samples out of 35,136, which is still significant and would not prevent a Gaussian distribution. However, a low recovery rate at this low level means that there are difficulties linked to ground clutters echoes and a possibility for some of the kept data to be also polluted. Strong ground clutter echoes prevent discrimination between the radar

ground echoes peak spectrum and the radar meteorological peak spectrum when the wind intensity is weak. The effect is an under estimation of the wind weakest values. The pre-monsoon period is the period that is the most affected by ground clutter echoes since, this transition period experiences an alternation between the southwestern monsoon wind during the night and the northeastern Harmattan wind during the day, linked to the proximity of the ITD (intertropical discontinuity). As explained in Ref. [1], this discontinuity between the two air masses is characterized by weak horizontal wind and stronger vertical wind. This effect is still more obvious by daytime and enhances the difficulty to discriminate the meteorological peak spectrum within the radar signal. The Niamey distributions also show weak daytime winds during the pre-monsoon period (Fig. 2d), but the Niamey radar is less polluted by ground echoes (the data recovery rate is 96%). The other transition period (post-monsoon) also shows numerous weak wind values in Bamako, especially during daytime (Fig. 4a).

It is however noted that the under estimation of the wind potential under low wind conditions should remain weak: according to the results of Ref. [1], the discrepancy should not be larger than 1 m·s<sup>-1</sup> on average. Taking the true values would shift the calm wind bin to values that lie under or just above the cut-in speed of the selected turbines (see next section). Considering that the wind power is a cubic function of the wind speed (between the cut-in and rate speed of the turbine), a slight shift in the distribution should not much affect the wind power.

In most other cases, the Weibull probability distributions match the observed distributions. The distributions are close to a Gaussian distribution ( $1.7 < k < 2.3$ ) in about half the cases. However, there are some cases when the Weibull distributions fail to represent the observations, even if  $k$  is close to 2. They fail when the observed distributions are bimodal, as during the pre-monsoon period in Niamey (Figs. 2d-2f) or during the dry season in Bamako (top of Fig. 5). In

Bamako, the bimodal distribution (Fig. 5, top) is linked to the strong variation in the wind intensity between November and December as can be seen in Fig. 2a (the distribution includes both months). The mean wind velocity at 150 m grows from  $5 \text{ m}\cdot\text{s}^{-1}$  to  $7.5 \text{ m}\cdot\text{s}^{-1}$ . Nighttime and daytime winds grow, but the increase is larger for nocturnal winds. There are in fact two distributions that merge to give the dry season bimodal distribution. In Niamey, the bi-modal distribution of the pre-monsoon transition period is linked to the different characteristics of the wind between April and May by day. April is less prone to the alternation between monsoon and Harmattan winds: the Harmattan wind blows days and nights and is slightly higher during the day than in May (Fig. 1d). So the daytime distribution shows a second peak during the daytime (Fig. 2d), corresponding to this month, that is also seen in Fig. 2f. In these cases, the Weibull distribution is not representative of the observations.

The distributions for the monsoon period (Fig. 3) are the closest from Gaussian distributions. The NLLJ is weaker during the monsoon and the diurnal wind is enhanced, compared to the pre-monsoon diurnal wind, due to the decrease in the turbulence between both periods [31]. Consequently, differences between day and night decrease and the distributions become more Gaussian at both sites.

This paragraph shows analyse of the Weibull coefficients presented in Table 2. In reminder, the parameter  $c$  is related to the mean wind. Not surprisingly, the evolution of the  $c$  coefficients is in conformity with the monthly results seen earlier (Fig. 1) and seasonal wind mean values presented in Table 3. The coefficient  $c$  values are most of the time slightly larger than the corresponding mean values: 11.3% to 11.9% in average at Bamako and Niamey respectively by day, and 11.5% and 12.5% by night. A 12% increase in the mean wind should produce a 40% increase in the wind power, for a Gaussian distribution. This anticipates that the Weibull distribution estimations would yield higher wind powers than the observed

**Table 3** Values of wind speed and wind power obtained during day, night and during the whole diurnal cycle, at 210, 150 and 90 m agl (from top to bottom), at Bamako and Niamey. \* Weibull hybrid distribution is used.

	Wind speed ( $\text{m}\cdot\text{s}^{-1}$ )			Wind power ( $\text{W}\cdot\text{m}^{-2}$ )		
	Day	Night	Full cycle	Day	Night	Full cycle
Bamako	2.9	5.4	4.3	*37/53	189/200	131/137
Pre-monsoon	2.2	4.4	3.5	*19/31	120/125	*68/85
	1.6	3.4	2.6	*10/20	*63/78	*37/53
	3.7	5.0	4.2	61/75	120/127	86/98
Monsoon	3.0	4.0	3.5	33/39	70/74	49/54
	2.4	3.2	2.7	*18/27	48/49	*28/37
	3.8	5.5	4.6	54/59	145/148	97/101
Post-monsoon	3.2	4.5	3.8	33/37	88/91	59/62
	2.5	3.5	3.0	18/24	57/58	38/40
	5.6	8.5	7.2	205/213	557/548	401/400
Harmattan	4.8	7.3	6.2	138/138	397/388	281/276
	4	6.2	5.2	*84/98	297/283	211/201
Niamey	5.1	7.4	6.2	160/160	347/340	254/249
Pre-monsoon	4.7	6.7	5.7	156/150	254/249	207/200
	4.4	5.9	5.2	196/168	218/214	210/195
	4.4	6.3	5.4	84/87	209/212	153/162
Monsoon	4.0	5.3	4.7	72/75	127/132	103/108
	3.7	4.3	4.0	69/69	86/97	82/91
	3.5	5.6	4.6	42/43	155/153	98/98
Post-monsoon	3.3	4.9	4.1	38/39	98/97	68/68
	3.1	4.2	3.6	39/38	68/68	54/53
	6.3	9.7	8.0	197/195	711/703	448/450
Harmattan	6.2	8.4	7.3	194/192	438/434	316/313
	6.1	7.2	6.6	211/203	284/280	248/242

distributions ones. Next section will show that this effect is damped down by other factors such as  $k$  or some high wind values with weak but not null probabilities in the observed distributions.

In addition, the distributions become increasingly narrow on both sites ( $k$  increases), whatever the hour, between the pre-monsoon, the monsoon and the post-monsoon. This trend continues in winter at Niamey. The value of the couple ( $c, k$ ) is optimized for wind energy when  $c$  values are high and  $k$  is low (but still close to 2) because it reflects a broad range of high winds. This does not seem to be the case of this work's observed distributions, which show narrower distributions for stronger winds. This tendency is even more marked in Niamey than in Bamako. The distributions are always more narrow by nighttime than by daytime. Finally,  $k$  systematically increases from the 90 m-level to the 210 m-level which there again

compensates the  $c$  increase.

In conclusion, the Weibull or hybrid of Weibull distributions well account for the observed distributions except when the latter are bimodal during the pre-monsoon in Niamey or during the dry season in Bamako. The wind potential can therefore be studied using both the Weibull and observed distributions.

## 5. Wind Power

### 5.1 Wind Power Density of the Sites

The recoverable wind power of a site is proportional to the cube of the average wind speed. It can be obtained from the Weibull parameters  $c$  and  $k$  (Table 1) or directly deduced from the observed distribution (Eq. (12)). The air density is taken as the monthly average of the air density measured at 10 m by the United States of America Atmospheric Radiation Measurements mobile facility, at the Niamey airport. The wind power (in  $W \cdot m^{-2}$ ) is independent of the turbine characteristics. Table 3 lists the seasonal mean wind speed and the wind power obtained during day, night and during the whole diurnal cycle, at the 3 levels, at Bamako and at Niamey.

Firstly, it will consider the differences between the two methods for computing the wind power at 150 m (Table 3). The results obtained by the two methods are roughly equivalent for most cases (differences smaller than 5%) except during the pre-monsoon period in Bamako where the discrepancy reaches 20%, mostly on account of daytime values. The difference is linked to the mismatch exhibited above between the Weibull and the observed distributions (top of Fig. 2). Anyway in this case, both calculations are underestimated, due to the under-estimation of the weakest wind values during daytime.

It can also be noted that in most cases, the wind power calculated from the Weibull coefficients is slightly underestimated, compared to the wind power integrated from the observed distribution. In fact, the calculation of the wind power from the observed distributions can be greatly increased by high values of wind speed (as a cubic function of the wind speed).

High wind speed values, even if not frequent, were encountered during the monsoon convective events for instance. These high wind values are not reproduced in the Weibull distributions that rapidly reach 0 at high wind values.

Table 3 confirms the result found previously of an optimal wind potential during the dry period at both sites. In Bamako at 150 m and during the whole day, the wind speed increases roughly 1.8-fold from the pre-monsoon to the dry period ( $3.5 \text{ m} \cdot \text{s}^{-1}$  to  $6.2 \text{ m} \cdot \text{s}^{-1}$ ) while the wind power increases 3.2-fold ( $85 \text{ W} \cdot \text{m}^{-2}$  to  $276 \text{ W} \cdot \text{m}^{-2}$ ). In Niamey from the post-monsoon to the dry season, the wind velocity also increases 1.8-fold ( $4.1 \text{ m} \cdot \text{s}^{-1}$  to  $7.3 \text{ m} \cdot \text{s}^{-1}$ ) whereas the wind power increases 4.6-fold ( $68 \text{ W} \cdot \text{m}^{-2}$  to  $313 \text{ W} \cdot \text{m}^{-2}$ ). The difference between the two cases essentially comes from the wind cubic function of the wind speed and in the wind speed mean value increase between Bamako and Niamey.

On the other hand, it is noted that wind powers available are very close at Niamey and at Bamako in winter ( $276 \text{ W} \cdot \text{m}^{-2}$  and  $313 \text{ W} \cdot \text{m}^{-2}$  for the whole diurnal cycle), despite the stronger average wind speed at Niamey ( $7.3 \text{ m} \cdot \text{s}^{-1}$  at Niamey for  $6.2 \text{ m} \cdot \text{s}^{-1}$  at Bamako). This comes from the flatter shape of the distribution in Bamako ( $k = 1.86$  at Bamako and  $2.98$  at Niamey), which favors Bamako.

In addition to the winter time, the pre-monsoon period is also interesting at Niamey:  $200 \text{ W} \cdot \text{m}^{-2}$  for the whole cycle (the wind power is two-fold that of the monsoon period). It previously has reservations about the pre-monsoon at Bamako (Section 3 and this section) due to the weakness of the wind during the day. The results over the whole diurnal cycle, however, show that the NLLJ compensates for the diurnal weaknesses, so that the wind power over the whole cycle is higher than that of the monsoon period ( $85 \text{ W} \cdot \text{m}^{-2}$  for  $54 \text{ W} \cdot \text{m}^{-2}$  during the monsoon). The post-monsoon period is the least interesting at both sites. The wind power over the whole cycle is only  $62\text{-}68 \text{ W} \cdot \text{m}^{-2}$ .

Kebe et al. [32] performed one year of wind

measurements at a coastal site in northern Senegal (west Africa), on a 40 m tower. They found a mean wind speed of  $4.8 \text{ m}\cdot\text{s}^{-1}$  ( $5.6 \text{ m}\cdot\text{s}^{-1}$ ) during the rainy (respectively the dry) season, corresponding to a wind potential of  $100 \text{ W}\cdot\text{m}^{-2}$  ( $130 \text{ W}\cdot\text{m}^{-2}$ ). If it considers the increase in the potential relative to the season, their results are similar to those obtained in this work, which could be expected since the main wind regimes are common to both sites (Harmattan and monsoon). However, their site also benefits from the influence of the sea breeze, which produces enough wind at 40 m and would require cheaper technology.

For the comparison of the wind power between the different levels, it can be noted that, the wind power is usually calculated at the hub height. Taking into account the large vertical wind gradients that can be observed below the nocturnal low level jet (up to  $5 \text{ m}\cdot\text{s}^{-1}$  per 100 m as shown in Ref. [1]), it can be interesting to look at what is observed at the extremities of the blades. Table 3 shows that the wind power calculated at 210 m is on average 2.4-fold the wind power at 90 m during nighttime or daytime in Bamako, 1.7-fold in Niamey for the whole day and 2.1-fold at nighttime. This is much higher than the vertical divergence usually encountered for logarithmic profiles, except under very strong turbulent dynamic conditions. As mentioned in Ref. [1], it may wonder whether these very large wind gradients would provoke a premature wearing out of the turbine blades.

### 5.2 Wind Power Output from the Wind Turbines

To be able to compute the mean monthly power output in order to assess the energy efficiency, it is necessary to define the wind turbines that are going to be used. When selecting the wind turbine models, it has to face too competitive criteria: the necessity to choose high hub heights and small cut-in and rate turbine wind

speeds. Usually, high turbines are used in very windy regions, which shift the characteristic speeds of the turbines to higher values of wind speed. The Vestas V-112 [33] and Enercon E-80 [34] were the only models to fulfil both criteria (Table 4). As a consequence of the high hub height which allows a very large swept area, they are high power turbines, probably oversized for the purpose of this study. The objective here is to quantify the performances of these two turbines in the environment of this study.

The power curves of each turbine have been merged with the wind speed distributions, using Eq. (14) to retrieve  $P_T$ . In addition, it calculated  $A_f$ , the availability factor and  $C_f$ , the capacity factor.  $A_f$  is the integral of the wind distribution curve ranging from the cut-in and cut-out speeds.  $C_f$  is the ratio between  $P_T$  and the rated power [35].

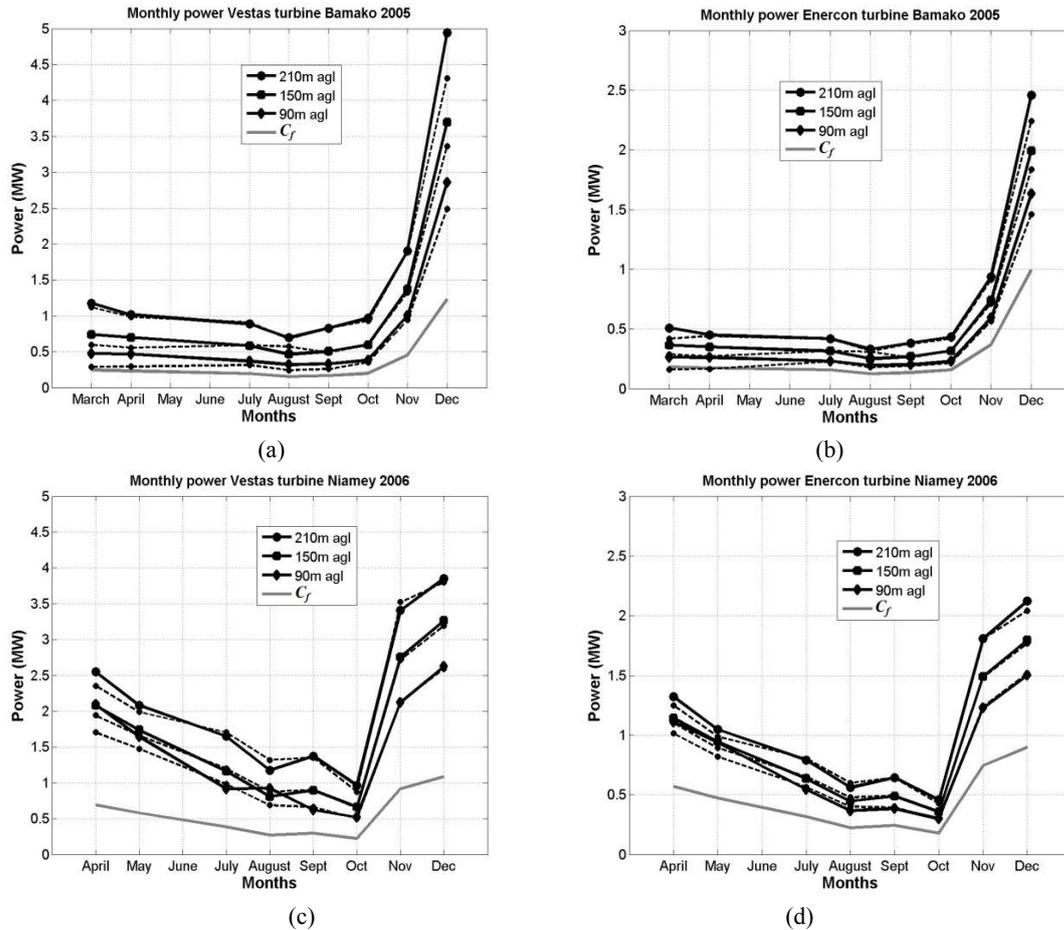
The availability factor is the worst at Bamako for the Vestas turbine, whose cut-in speed is  $4 \text{ m}\cdot\text{s}^{-1}$ . It ranges between 0.41 and 0.55 during most part of the year, except in winter where it reaches 0.84. This means that for most months, this turbine will work less than half the time. Due to the smaller cut-in speed of the Enercon turbine, the latter will progressively work 58% of the time in March to 87% in December. The performances are better in Niamey where the wind conditions are more favourable.  $A_f$  varies from 0.72 to 0.97 (except 0.65 in October) for the Vestas turbine and from 0.80 to 1 for the Enercon, which represents very good functioning conditions [35].

The monthly variations of  $P_T$  (in MW), according to the wind turbine model, are represented in Fig. 6, at the three levels, based on the observed distribution or the Weibull distribution, along with the corresponding  $C_f$ .

The difference between both distributions is negligible except in April and May at Bamako. The wind power output is almost constant throughout the

**Table 4** Technical characteristics of the two wind turbines (Vestas and Enercon).

Wind turbines	Rated power (kW)	Cut-in speed ( $\text{m}\cdot\text{s}^{-1}$ )	Rated wind speed ( $\text{m}\cdot\text{s}^{-1}$ )	Cut-out speed ( $\text{m}\cdot\text{s}^{-1}$ )	Hub height (m)	Rotor diameter (m)	Swept area ( $\text{m}^2$ )
Vestas V-112	3,000	3	12	25	119	112	9,852
Enercon E-82	2,000	2	13	28	138	82	5,281



**Fig. 6** Monthly variations of wind power output (left) for the Vestas turbine, (right) for the Enercon turbine, at (top) Bamako and (bottom) Niamey. Full black lines refer to the computation from the observed distributions and dotted lines refer to the one with the Weibull distributions. The  $C_f$  capacity factor is also represented (grey lines).

year in Bamako, except during November and December, whereas it decreases from April to October in Niamey, increasing again in November and December.  $C_f$  values that range between 0.15 and 0.25 before November in Bamako indicate that the 3-MW Vestas turbine would work under a regime which is much below its rate power during most part of the year. It is somewhat better in Niamey, especially during April and May when  $C_f = 0.69$  or  $0.58$ . Note that Ref. [34] indicates worst capacity factors ranging in 0.13-0.16, at 75 m, for a coastal site in Italy. On the opposite, the winter months exhibit attractive conditions of working for the Vestas turbine since  $C_f$  reaches 1.23 in Bamako and 1.1 in Niamey. The 2-MW Enercon turbine is also oversized for the Sahel wind conditions. During most of the year:  $C_f$  is around 0.16

in Bamako and in the range 0.15-0.57 in Niamey. It reaches 1 and 0.9 in winter.

Due to the different sizes of the rotors between both models of turbine and although the Enercon turbine would work longer than the Vestas would, the cumulated energy is roughly twice as large for the Vestas as for the Enercon, whatever the site (Fig. 6).

This study shows that the strongest values of LLJ are encountered during winter, which corresponds to the dry season or during the transition period between the dry and the wet seasons. Associated with these strong values of LLJ, large wind shear, either in magnitude or direction, appears in the vicinity of the nocturnal jet. The probabilities of strong wind shear are most important between 150 m and 270 m. In the LLJ period, in Niamey it found 60% of cases of shear higher than 4

$\text{m}\cdot\text{s}^{-1}$  per 100 m between 150 m and 270 m and 20% between 270-500 m. Shears higher than  $4 \text{ m}\cdot\text{s}^{-1}$  per 100 m appear in Bamako, where the pre-monsoon wind shear frequencies vary from 10% to 20% at  $4\text{-}6 \text{ m}\cdot\text{s}^{-1}$  per 100 m, at the LLJ time (21H00 to 06H00). There are even cases, but less probable, where the wind shear can reach  $6\text{-}8 \text{ m}\cdot\text{s}^{-1}$  per 100 m. In Niamey, the period to worry is between 03H00 and 06H00, which corresponds to the maximum of the LLJ. These shears of low layers are the most dangerous for the aircrafts. Both profilers were located in the airport area, which enabled accurate information to be provided to the pilots, who otherwise received conflicting measurement indications from their on-board instruments and the control tower.

## 6. Economic Study

This section presents an economic study of the wind energy project at the site of Niamey. First, an estimation of the number of wind turbines needed to meet the energy demand of Niamey is given. Then, an analysis of the leveled cost of the energy produced (average cost per kWh produced) is presented. A comparison of the price of the kWh with the price for other energy sources concludes this study.

### 6.1 Estimation of the Number of Wind Turbines Needed to Meet the Energy Demand of Niamey

A software developed by the National Renewable Energy Laboratory (and maintained by HOMER Energy), called HOMER (version 2.67 beta, Ref. [36]) is used, to find out what costs are associated with converting wind energy and to estimate the number of wind turbines needed to meet the energy demand of Niamey city.

The software requires the monthly wind speed average for the 12 months of the year, so it supplemented the missing months (January, February, March and June) by interpolating the wind speed average for the other months. This interpolation has been justified by the results of Lothon [37] who

analyzed the radiosoundings of the 2006 AMMA (African Monsoon Multidisciplinary Analysis) experiment. It checked that the winter time vertical profiles of the wind speed were similar and that June was characteristic of the pre-monsoon transition period between April and July.

The number of wind turbines needed to meet the energy demand varies according to the energy demand itself (the load) and to the wind energy potential available at the site. The energy demand data are those from 2008, provided by the Société Nigérienne d'Electricité (NIGELEC). They are presented with vertical bins in Fig. 7 along with the number of wind turbines needed to meet the energy demand for both wind turbines.

During the Harmattan season from November to February, the energy demand is low in Niamey since the air is cooler and air conditioners are not needed. This is nevertheless the period with the highest wind energy. So the number of wind turbines required is only 10 to 14 for the Vestas wind turbines and 17 to 27 for the Enercon. During the pre-monsoon period (April to June), the demand is high again since temperatures increase, but the potential is also high. Although the demand decreases slightly during the rainfall period (July to September), the wind potential is smaller and the number of wind turbines increases until the post-monsoon (October), when the energy demand is maximal since temperatures climb again at the end of the monsoon season, under still humid conditions. Unfortunately, the wind energy potential is minimal at this period of the year, so the number of wind turbines needed amounts to 100 for the Vestas and 184 for the Enercon, which is quite a lot.

This computation does not include any characteristics of the diurnal cycle, which means that the results imply a large storage capacity able to store the energy produced at night, and release it during the day. In fact, the energy demand is the highest during the daytime (NIGELEC source, not shown here) whereas the wind potential is the highest during the

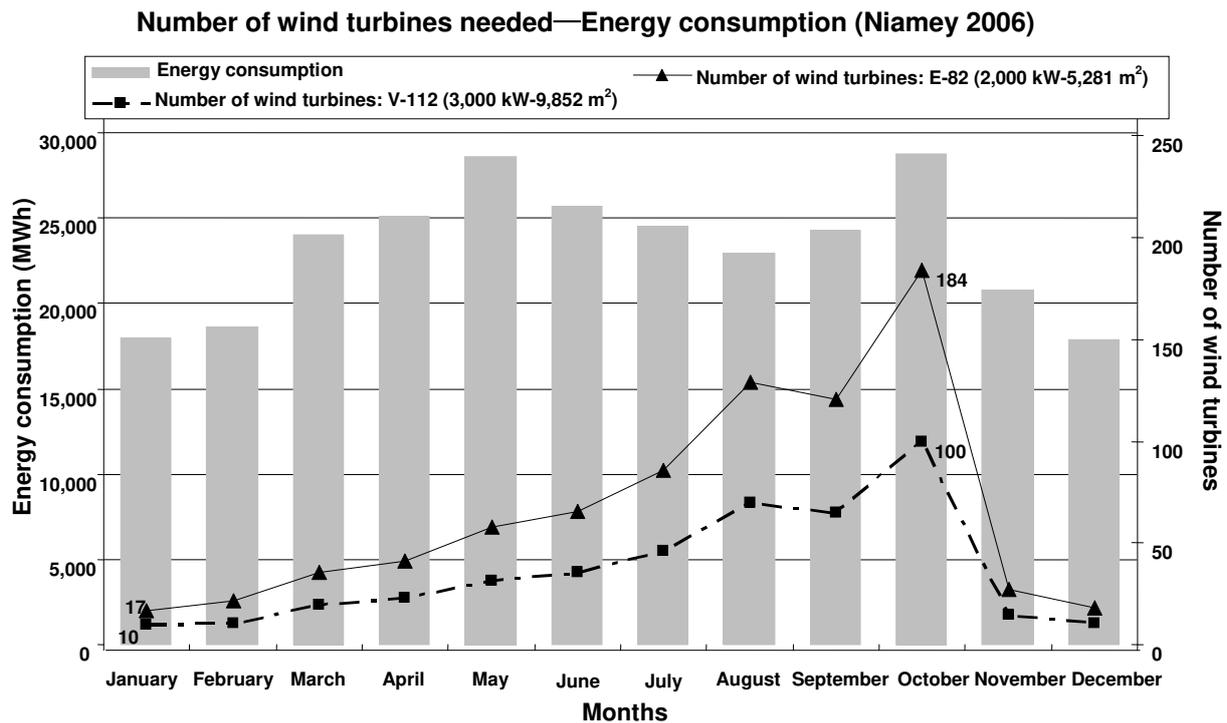


Fig. 7 Number of Vestas V-112 and Enercon E-82 wind turbines needed to meet the Niamey energy demand.

night. Unfortunately, this type of storage can not work from one season to another because storing electricity over a long period is still impossible.

### 6.2 Leveled Cost of Energy Analysis

The economic analysis of a wind system allows the leveled cost of energy to be determined in €/kWh (an economic assessment of the cost of the energy-generating system including all the costs over its lifetime) from the total net present cost and the total energy produced (kWh) throughout the period of project operation. The total net present cost includes: investment costs, operation and maintenance costs, and the cost of borrowing the capital employed. The fuel cost and the disposal-of-waste cost are zero in case of wind energy.

It is noted that the values fluctuate, since the construction costs, the operating costs and the borrowing costs vary in space and time. The total net present cost does not include the various taxes (value added tax, community tax, contribution rate routing network, etc.) or the marginal external costs due to the

emissions of greenhouse gases, or those relating to the preservation of health. So, this total net cost is not the purchase price per kWh to the consumer (price all taxes combined).

Table 5 presents the leveled cost of energy (€/kWh), the lifetime of the project and the greenhouse gases emission rates according to the two types of wind turbines selected. It is also noted that, for each case study, some DC/AC (direct current/alternating current) converters with a total capacity of 60 MW and a lifetime of 20 years are used to invert the current delivered by the wind turbines into alternating current. Solar batteries (32,320 batteries), each with a capacity of 1,900 Ah (7.6 kWh) and a 10-year lifetime, are also used for storing the energy before transition to the network.

The results analysis shows firstly that the leveled cost of energy decreases with the size of the wind turbine (rated power, swept area). Moreover, this cost ranges from 0.093-0.129 €/kWh, which, even if it seems high, is within the range of the leveled costs often indicated in the literature. In 2004, according to a study by the World Energy Council, the leveled cost of

**Table 5 Total net cost, lifetime of the project, leveled cost of energy and emission rates of greenhouse gases for the two types of wind turbines selected.**

Type of wind turbines	Number of wind turbines needed	Total net present cost (€)	Lifetime of the project (year)	Leveled cost of energy (€/kWh)	Emission rates of greenhouse gases (kg/year)
Vestas V-112	100	92,237,418	20	0.093	0
Enercon E-82	184	117,341,553	20	0.129	0

**Table 6 Comparison between the leveled cost of wind energy and that of other energy [38].**

Energy sources	Leveled cost of energy (€/kWh)
Fossils fuels (coal, oil, gas)	0.02-0.04
Nuclear	0.02-0.037
Hydropower	0.02-0.12
Wind energy	0.03-0.13
Solar photovoltaic energy	0.25-1.6
Biomass energy	0.03-0.12
Marine energy	0.08-0.40
Geothermal energy	0.02-0.10

energy of large wind power installations varied from 0.03 €/kWh to 0.13 €/kWh [38]. Ngala et al. [39], in a 0.311 €/kWh to 0.388 €/kWh for a very windy site and from 0.466 €/kWh to 0.621 €/kWh for a less windy site.

For comparison, the basic rate of electricity (all taxes included) in Niger has been 0.12 €/kWh for over 20 years. This makes the alternative of wind energy quite competitive. It is noted that the external costs due to emissions of greenhouse gases and those related to preserving the health of populations will be null or at most very small. Wind energy is a “clean energy”. But it should also be noted that, after 10 years of the 20-year lifetime of the project, the batteries will have to be changed. The cost is included but this represents a non-negligible source of pollution.

### 6.3 Comparison of the Price per kWh after the Pith with the Price of Other Energy Sources

Whether, it comes from thermal, nuclear, geothermal, hydro, wind, photovoltaic, biomass, tidal, or other sources, electricity is the main vector of any economy. The current used here is the conversion of energy sources into electricity (final offer). Thus, comparing the leveled cost of energy is of major interest since it is through this cost that the new sources of energy will be judged competitive. Table 6 shows a

comparison between the leveled cost of wind energy and that of other energy sources.

This table shows that the leveled cost of wind energy although still higher than that of fossil energy sources (coal, oil or gas) and the large chains (nuclear and hydroelectric), remains competitive, and more competitive than the costs of other renewable energy sources.

## 7. Conclusions

The analysis of the characteristics of the wind speed on the two sites shows that the variations of wind speed depend on the dynamic and thermal environment at synoptic scale. The wind direction depends strongly on the annual alternation between the monsoon (west southwest) and the Harmattan (east-northeast) winds. The Harmattan period is very propitious for wind energy production throughout the whole day, with sites wind power exceeding  $300 \text{ W}\cdot\text{m}^{-2}$  due to high wind speeds. During this period, the conditions are optimal since wind speed is very steady and turbulence is low, which prolongs the life-time of the wind turbines. However, as highlighted in Ref. [1], further investigations should be made of turbine wear linked to dust events in the Harmattan periods. Other periods favorable for wind energy production are: the nights and early mornings during the pre-monsoon and the monsoon periods, in Bamako, with a power exceeding  $100 \text{ W}\cdot\text{m}^{-2}$  due to the nocturnal low-level jet, which can produce strong enough wind at 150 m. The pre-monsoon and monsoon periods are favorable during the whole day in Niamey. The post-monsoon is the least propitious for this energy production.

The Weibull distribution function, as in many other previous works, revealed to be a good tool to evaluate the wind power. In agreement with Weisser [18] and

this study, it can insist upon the necessity to assess the diurnal variation of the wind velocities, and to compare it with load duration curves of electricity demand. In many studies calculations are based solely on daily averages. In the case of this work, this would lead to an underestimation of wind potential at night and an overestimation during daytime hours.

It can be found that the period of the highest demand in Niamey unfortunately does not correspond to the period of highest wind potential. To solve this problem, a high storage capacity has been anticipated. In addition, the fact that the nocturnal jet does not blow at low level but starts to be strong enough at 150 m agl implies high-performance wind turbines. The economic study showed that, in spite of these drawbacks, the leveled cost of energy resulting from this study spans 0.093-0.137 €/kWh. Although this exceeds the costs for large chains of electricity production, it remains competitive with the other renewable energy sources. In Niamey, it is even comparable to the basic rate currently charged (the energy is mainly from fossil sources, imported from Nigeria).

The main issue of this study is the necessity to store the energy from nighttime to daytime. The number of batteries that is required to do so is clearly unrealistic. Other technologies could be considered, including pumped hydro storage, compressed air energy storage or hydrogen production [40]. However, any of them would require sophisticated technology, which would increase the production cost. According to Sovacool [41], who promotes the use of several renewable energies to solve the intermittency problem, the best outcome would probably be the combination of the nighttime wind energy with the daytime solar energy. This issue will be considered in a future work.

### Acknowledgments

The authors of this work were supported by INSU-CNRS and the University Abdou Moumouni (Niamey, Niger). Based on a French initiative, AMMA was built by an international scientific group and is

currently funded by a large number of agencies, especially from France, UK, United States of America and Africa. It has been the beneficiary of a major financial contribution from the European Community's Sixth Framework Research Programme. Detailed information on scientific coordination and funding is available on the AMMA international web site: <http://www.amma-international.org>. The authors would like to give special thanks to ASECNA for carrying out the radiosounding operation in Bamako and providing the UHF profiler data in Bamako. The authors also thank the U.S. Department of Energy as part of the Atmospheric Radiation Measurement Program for operating the radiosounding and UHF wind profiler in Niamey and providing the data.

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