Analysis of wind data and wind energy potential along the northern coast of Senegal

I. Youm [1], J. Sarr [2], M. Sall [2], A. Ndiaye [1] and M.M. Kane [1,2]

[1] Laboratoire des Semi-conducteurs et d'Energie Solaire, Faculté des Sciences et Techniques, Université Cheikh Anta Diop, Dakar-Fann, Sénégal
[2] Centre d'Etudes et de Recherche sur les Energies Renouvelables (CERER), B.P. 476, Dakar, Sénégal

Abstract - *Senegal is one of the developing countries and its dependence upon imported fossil fuels can only be offset by the sustained exploitation of its indigenous resources. Wind energy is renewable and environment friendly, which can be harnessed for various end-uses. A precise knowledge of wind energy regime is a pre-requisite for the efficient planning and implementation of any wind energy project. However, due to the absence of a reliable and accurate Senegalese Wind Atlas, further studies on the assessment of wind energy in Senegal are necessary. The main purpose of this paper is to present and to perform an investigation on the wind energy potential of the northern coast of Senegal along the Atlantic Ocean. Therefore, in this study, wind data collected over a period of two years at five different locations in this region of Senegal were evaluated in order to figure out the wind energy potential along the northern coast of Senegal. The data from selected stations were analyzed using the two-parameter Weibull probability distribution function. With an annual mean wind speed of 3.8 m/s, an annual energy of 158 kWh/m^2 could be extracted. It is found that the potential uses of wind energy in these locations are for water pumping in rural areas. The study presented here is also an attempt to promote wind energy in Senegal and to bridge the gap in order to create prospective Wind Atlas of Senegal.*

Résumé - *Le Sénégal est un des pays en voie de développement et sa dépendance en combustibles fossiles importés peut être facilement compensée par une exploitation soutenue de ses ressources nationales. L'énergie éolienne est une énergie renouvelable et avec un environnement adéquat, peut être facilement exploité pour divers usages finaux. Une connaissance précise du régime en énergie éolienne est un préalable efficace pour la planification et l'exécution de n'importe quel projet en énergie éolienne. Cependant, en raison de l'absence d'un atlas fiable et précis en matière de vent au Sénégal, des études portant sur l'évaluation du potentiel en énergie éolienne au Sénégal sont nécessaires. Le principal objectif de cet article est de présenter et effectuer une recherche sur le potentiel en énergie éolienne sur la côte au nord du Sénégal le long de l'Océan Atlantique. Par conséquent, dans cette étude, des données de vent collectées sur deux années sur cinq sites différents dans cette région du Sénégal ont été donc évaluées pour y connaître le potentiel en énergie éolienne le long de la côte au nord du Sénégal. Les données des stations choisies ont été analysées en utilisant la fonction de distribution de probabilité de Weibull à deux paramètres. On constate que les utilisations potentielles de l'énergie éolienne dans ces endroits sont pour le pompage de l'eau dans les régions rurales. L'étude présentée ici est aussi une tentative de favoriser l'énergie éolienne au Sénégal et d'en établir le lien pour l'élaboration éventuelle d'un atlas de vent du Sénégal.*

Keywords: Wind energy - Wind data - Weibull distribution - Wind energy potential - Senegal.

1. INTRODUCTION

The role of energy as a basic element of any economic development is well establishes and electric energy is an important index of a country's economical and technological progress. With poor fossil fuel reserves, Senegal depends heavily on imported oil and natural gas for its energy requirements. In the wake of the dwindling of fossil fuel reserves, rising coasts of this type of fuel and the negative environmental impacts such as air pollution, acid rain and greenhouse effects associated with it, renewable energy have gained great importance. Renewable energy resources have some advantages over fossil fuels; they are domestic, clean, free and inexhaustible. In this regard more work and effort have been put in developing solar and related energy resources [1]. However wind power has so far received only limited attention even though there are some Wind Energy Conversion Systems (WECS) in Senegal. These are used for various purposes but were installed subjectively without proper knowledge of the wind distribution in the respective areas in which they are operating. As a result, such systems were ignored and most of them were destroyed. Detailed knowledge of the wind characteristics is essential to allow optimizing the design and the usage of WECS.

This will be accomplished by using wind speed measurements. But this is a very difficult task, due to transitions in directions and speed of wind in most sites. Many studies have been completed to estimate the wind potential in different parts of the world. The work on wind data collection in Senegal dates back to 1970. The first published work on wind data was carried out on the basis of the monthly summaries of weather data recorded by the National Service of Meteorology (1979-1983) [2].

Senegal has over 12 weather stations located near an airport that routinely measure climatic parameters like solar radiation, sunshine hours, temperature, rainfall, atmospheric pressure, vapour pressure, wind speed and its direction, humidity. Despite routine meteorological data may overestimate wind speeds at a specific site, the tentative wind atlas obtained from this study have recognized the apparent coastal wind potential and provided valuable general information.

The aim of this paper is to further knowledge about the coastal wind resource by correlating the results of qualitative studies with statistical analysis of available records. Data gathered at five sites have been analyzed in order to support the evaluation and planning of future wind energy projects in this coastal region.

2. THEORETICAL BACKGROUND

2.1 Probability density function

Wind speed for a given location can be characterized by several probability density functions. For wind data analysis, the Weibull and Rayleigh probability density functions are commonly used and widely adopted [3-8]. Here, the Weibull density function is used to describe the wind speed frequency distribution. The Rayleigh distribution is a special case of the Weibull distribution. The general form of the two-parameter Weibull probability density function is mathematically expressed by [9]:

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \qquad (k > 0,\ v > 0,\ c > 1) \qquad (1)$$

where f (v) is the probability of having a wind speed of v (m/s), k is a dimensionless shape factor, and c is the Weibull scale factor with units of speed (m/s), which could be related to the average wind speed through the shape factor, k, which describes the distribution of the wind speeds. The relationship between the Weibull scale factor c, Weibull shape factor k and average wind speed v_m is given by the following formula:

$$v_m = c\,\Gamma\left(1 + \frac{1}{k}\right) \qquad (2)$$

where Γ is the usual gamma function.

The parameters k and c may be estimated by the linear regression of the cumulative Weibull distribution given by:

$$F(v) = 1 - \exp\left[-\left(\frac{v}{c}\right)^k\right] \tag{3}$$

2.2 Variation of wind speed with height

Wind speed generally changes with height, which requires an equation that predicts the wind speed at one height in terms of the measured at another height. Under normal conditions, a wind speed is greater at higher distance above ground. This is largely because the effect of surface features and turbulence diminishes as the height increases. The variability depends on distance from the ground and roughness of the terrain [9]. The most common expression accepted to describe the vertical variation of wind speed is expressed by a power law having the following form [9]:

$$\frac{v}{v_0} = \left(\frac{h}{h_0}\right)^{\alpha} \tag{4}$$

where v is the wind speed at the required height h, v_0 is w3ind speed at the original height h_0, and α is the surface roughness coefficient. The value of the exponent α varies from less than 0.10 over the tops of steep hills to over 0.25 in sheltered locations [10]. The typical value for flat coastal regions is 0.143, which is termed the one-seventh power law [11]. From measurements at different heights the exponent can be determined.

2.3 Wind energy potential

At a wind speed v, the available energy per unit area perpendicular to the wind stream over a given period of time t is expressed by the kinetic energy flux as [12]:

$$E_a = 0.5\,\rho\, v^3\, t \tag{5}$$

where ρ is the air density (kg/m^3) and E_a is the theoretical total energy available for doing work on the wind turbine. However, only a fraction of the total energy would be extracted. The maximum extractable energy from a system working at its optimum efficiency is limited by a coefficient of performance called the Betz limit (16/27 = 0.593). This capacity factor makes the extractable energy approximately 59.3 % of the theoretical energy and is given by [10]:

$$E_m = 0.2965\,\rho\, v^3\, t \tag{6}$$

3. WIND SPEED DATA

When compared globally with other regions of the world, the mean wind speeds in West Africa have been considered to be far below those of other regions [13]. According to previous work [2], the northern coastal area of Senegal may be considered the most promising locations where wind machines may be installed. The northern coastal plain of Senegal is a narrow strip of arable land, some 200 km long and 50 km in depth, representing 8,55 % if the country's total area. In this area called ‘’Niayes ‘’ there are very remote villages not hooked on the national grid. On the other hand, most of gardening activities in the country are concentrated in this area. The data from the coastal region in the North of the country were gathered at five sites, namely; Mboro, Ndandekhou, Pékesse, Pôtou and Makhana; three sites are near the coast where sea-breezes may influence the wind regime. The corresponding location of the sites investigated is shown on the map (Fig. 1).

These sites were selected on the basis that these rural areas constitute major agricultural belt. As water pumping for irrigation is identified as one of the viable application of wind energy, selection of these sites for the study was logical. The wind data are made up as time series and frequency statistics based on observations of wind speed and wind directions recorded every 10 min time intervals. Approximately two years of data is available for each selected site (1998-1999).

Long term measurements are needed for a good wind energy assessment. The longer the period of collected data the more reliable are the estimated wind potentials. However, as one year data is sufficient to predict the long-term trend of seasonal mean wind speed to within an accuracy of 10 % and a confidence level of 90 % [14, 15]. Hence the data collected could be used for a preliminary analysis to bring out useful conclusions on the wind regime characteristics of this region. It will be followed by a long-term measurement campaign.

Wind speed and direction used in this study were measured and collected by relatively and property maintained anemometer coupled to an electronic data-logger. Anemometers were mounted on poles at a fixed height above the ground, usually 10, 15, or 30 m. The data were used to evaluate frequencies of a certain wind speed as well as the monthly and annual mean wind speeds.

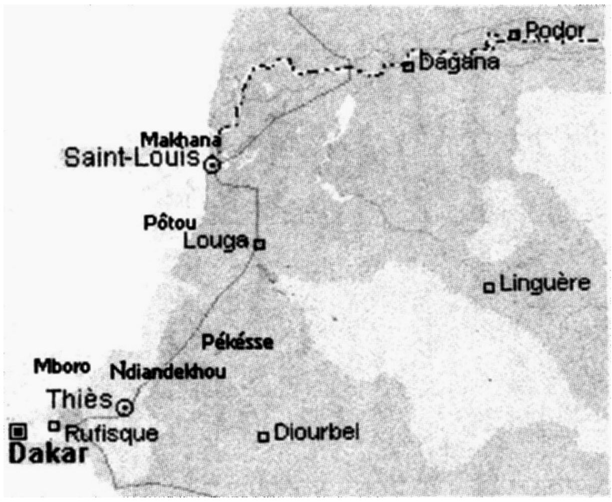

Fig. 1: Map showing the location of the sites utilized for this study

4. WIND DATA ANALYSIS

4.1 Wind speed variations

The wind at a given site usually varies frequently in direction and its speed may change rapidly under gusting conditions. Recorded wind speed data are generally available in time-series format. Each data recording represents an instantaneous wind speed and typical representative example of the results is provided by Fig. 2. An average of the hour-by-hour pattern can be derived from these records.

Variations of wind speed average on a daily basis at Mboro during April 1999 are plotted in Fig. 3. The pattern is predominantly random and during this month peaks of wind speed occur at different days with an average value of 4.1 m/s which is over the cut-in value of a typical wind machine.

Usually wind assessment is based on monthly mean wind speeds, because most of the wind system design calculations are performed on a monthly basis and that the wind has a relatively homogeneous behaviour within a month, even though monthly speed average may not reflect a reasonable estimate of wind power available at a given site. Daily and even hourly changes in speed must also be considered, although this is more difficult to analyze because of the wind's unpredictability [10].

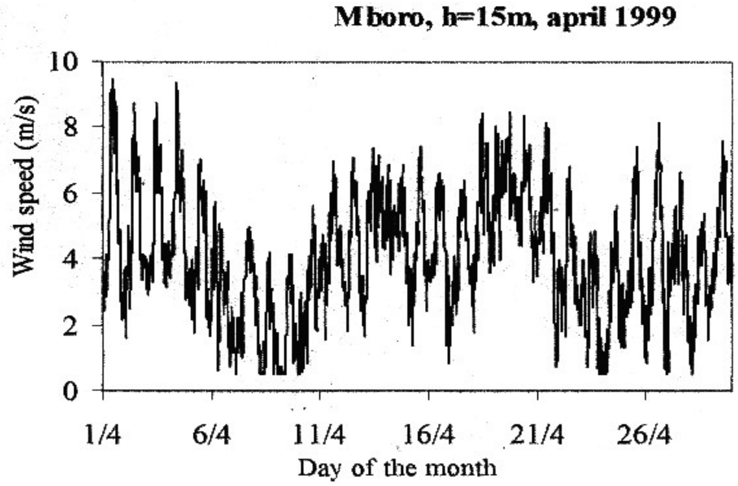

Fig. 2: Instantaneous wind speed recorded at 15 m height for the site of Mboro during April 1999

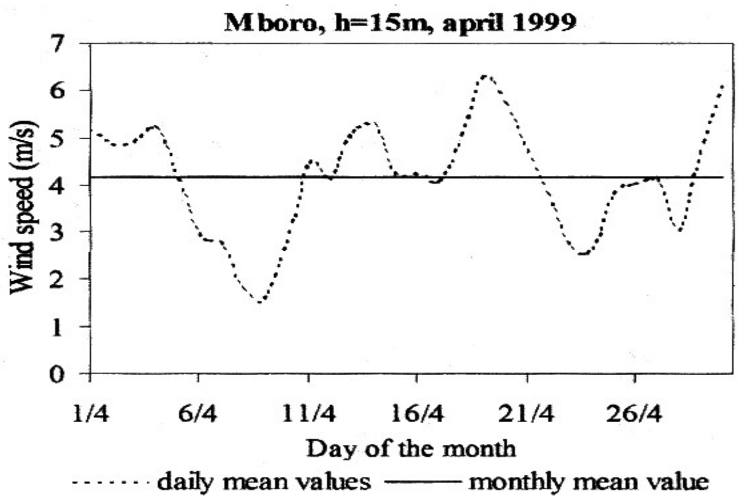

Fig. 3: Daily average wind speed variation at 15 m height for the site of Mboro during April 1999 and the monthly mean wind speed

The monthly average wind speed distribution exhibits seasonal trends with similar behaviour for all sites studied. The climate of Senegal has been defined as tropical and two distinct seasons are noticed in this region: a dry season (October-June) and rainy season (July-September). The seasonal movement of the inter-tropical convergence zone (ITCZ) is an important determinant of the duration and cessation of the rainy season in many tropical areas. The dry season can be further classified as: cool season January to March, hot season April to June and post-rainy season October to December.

Figure 4 illustrates the seasonal variation of the representative site of Mboro at height 15 and 30 m; slight difference in the monthly mean values have been noticed for these two different heights.

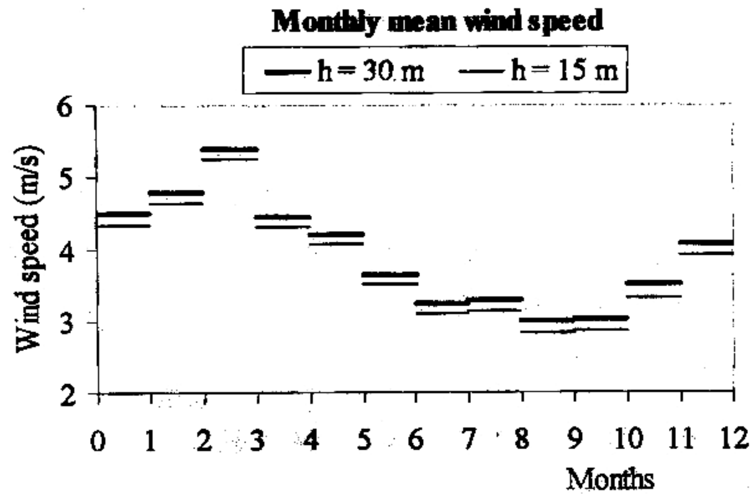

Fig. 4: Variation of the monthly average wind speed at 15 m and 30 m height for the site of Mboro

The resulting seasonal pattern in wind availability is characterized by high mean speeds during the dry but cold season and the maximum monthly mean wind speed of 5.3 m/s arises in March. The northern hemisphere winter is the dry season and at this time of the year, the country is largely under the influence of the strong northeast trade winds characterized by their steadiness, locally know as me ''Harmattan ''. The least windy months are generally July-October corresponding to the rainy and hot season.

During the rainy season, the ITCZ is at the most northerly position and the south-westerly monsoon brings cool and humid air masses from the southern Atlantic [16]. September and October have little wind as indicated by the lowest monthly mean wind speed value of around 3.0 m/s. Minimum wind speed limits for viable utilization for water pumping applications have been put at between 2,2 and 3,1 m/s [17].

Therefore, wind powered water pumping appears to be a viable option in almost all the study locations. Gardening activities along the coastal strip of Senegal depend mainly on underground water and start in November and is continued till May. It is fortunate that the winds in this region blow most strongly when they are wanted most. Hence wind powered irrigation projects will have an immediate impact during this period.

4.2 Diurnal variation of wind speeds

The diurnal variation of wind speed is a predominant feature discernible at many sites around the globe. Table 1 depicts the means of day and night wind speed for two selected stations for the year. From the data presented we see a big variation in day and night wind speeds. The diurnal bell-shaped trend is mainly attributed to localized variations induced by land or sea breezes; a characteristic which may be considerable, although the main imposing force is, always, the gradient wind of the day. The breeze and the gradient wind may superimpose, counteract, or more usually modify each other according to their relative strengths and directions.

4.3 Wind direction analysis

The month of March gives the maximum average value of wind speed in the North coast of Senegal during any calendar year. A histogram of the wind direction measurements for the site of Ndiandekhou during this windy month is shown in Fig. 5. From this figure we see that the probability of wind direction lying between 330°-30° is around 80 %. Analyses of the overall wind direction frequency for all the sites are depicted in Fig. 6.

Table 1: Day and night average wind speed in m/s on selected stations

		Mboro	**Makhana**
January	Day	5.10	5.92
	Night	3.60	4.68
February	Day	5.18	6.31
	Night	4.10	5.38
March	Day	6.17	6.58
	Night	4.31	5.86
April	Day	5.65	5.75
	Night	3.38	5.13
May	Day	5.28	5.76
	Night	3.19	4.92
June	Day	4.19	5.54
	Night	2.57	4.32
July	Day	3.76	4.67
	Night	2.61	3.44
August	Day	3.68	4.66
	Night	2.59	3.26
September	Day	3.31	4.10
	Night	2.37	3.21
October	Day	3.38	4.63
	Night	2.33	3.88
November	Day	3.88	4.72
	Night	2.76	4.26
December	Day	4.26	5.19
	Night	3.53	4.71
Annual mean	Day	**4.48**	**5.28**
	Night	**3.09**	**4.36**

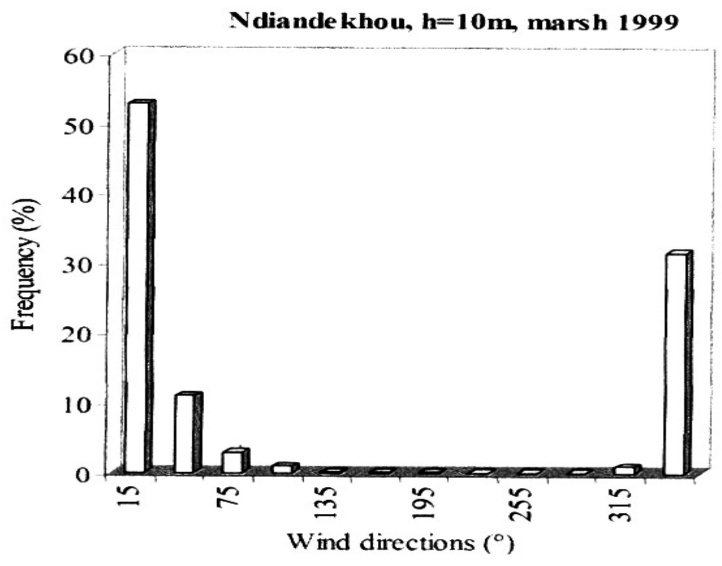

Fig. 5: Histogram of the observed wind directions
at 10 m height for the site of Ndiandekhou during March 1999

The prevailing direction of wind fall is from the North (north-north-west (NNW) to north-north-east (NNE) i.e. 330°-00 to 0°-300) which is more than 50 % of all the time. The frequencies of wind coming from the remaining sectors are insignificant. This wind characteristic is conforming to the general climatic features of the country. The prevalent wind patterns are defined by the moist-laden south-westerly winds from the Atlantic Ocean and the dry continental north-easterly from the Sahara Desert. These results are important when planning multi-wind turbine installation or in erecting single wind machine having windbreaks or obstacles upwind in the predominant sectors. On the other hand, the use of shrouded WECS can substantially increase the wind production [18].

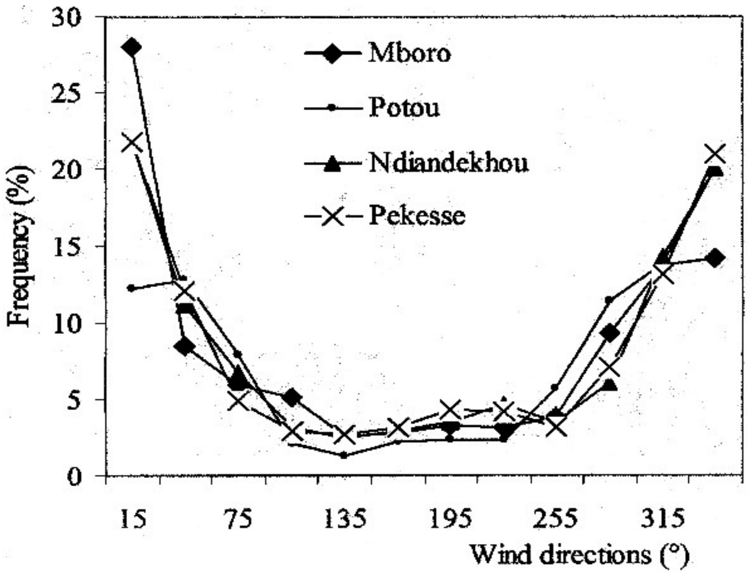

Fig. 6: Overall observed wind directions frequency for 4 sites

4.4 Analysis of wind speed frequency distribution

The frequency distribution of wind speed is essential in evaluating the availability of wind power at a site. It also permits the selection of appropriate wind machines for exploiting the wind for such application as water pumping for irrigation, grain grinding, etc.

Histograms of recorded wind speeds, shown in Fig, 7, exhibit a similar behaviour in all the station: the observed frequencies rise steadily, reaching a maximum value of the wind speed between 2 and 4 m/s, and then drop more or less slowly. Comparison between the two sites confirms that the site near the sea benefits more wind presence at higher speed. As there are no calms (zero wind speed) in the wind data, the monthly observed frequencies are compared with ones obtained by Weibull density distribution (Eq. l).

Example of the monthly observed and fitted wind speed distribution is depicted in Fig. 8. The similarity of both trends illustrates the good representation offered by such a model when compared to the actual measured data, However, the prediction of the overall or full term mean wind speed frequency distribution at 30 m height for Makhana did not match as closely that obtained directly from the data, as can be seen from Fig. 9.

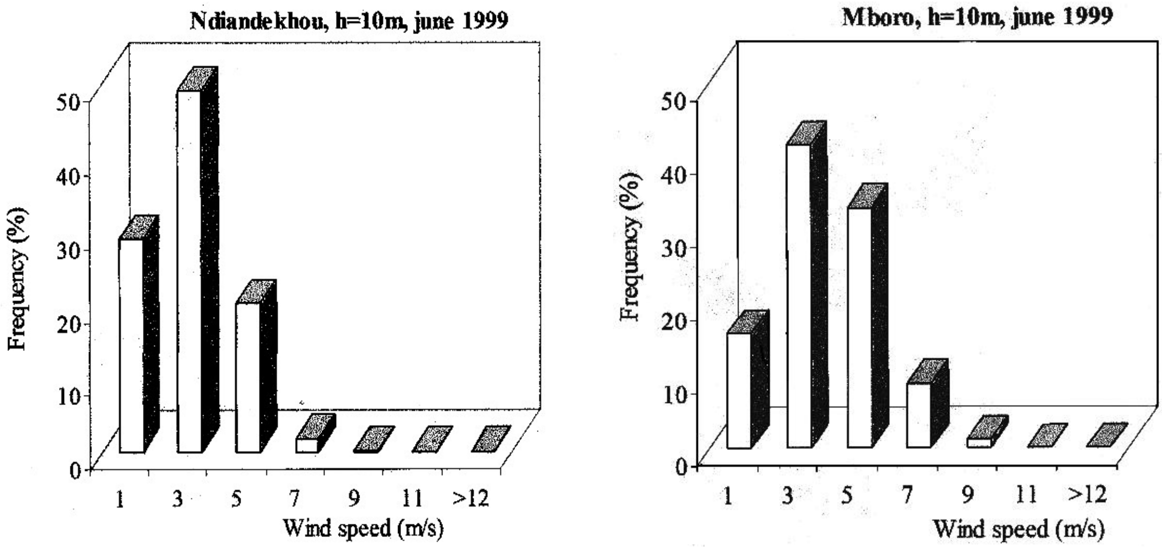

Fig. 7: Histogram of the wind speed distributions during June 1999
for the sites of Ndiandekhou and Mboro

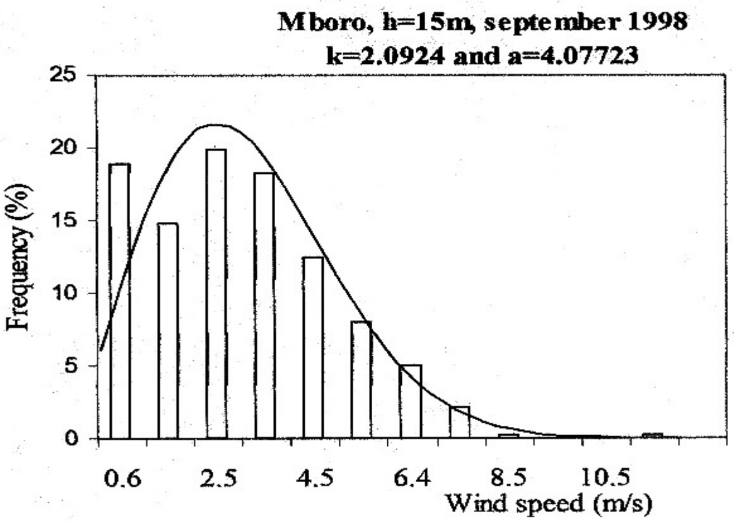

Fig. 8: Comparison of the monthly observed wind speed frequency
and wind frequency simulated by the Weibull function

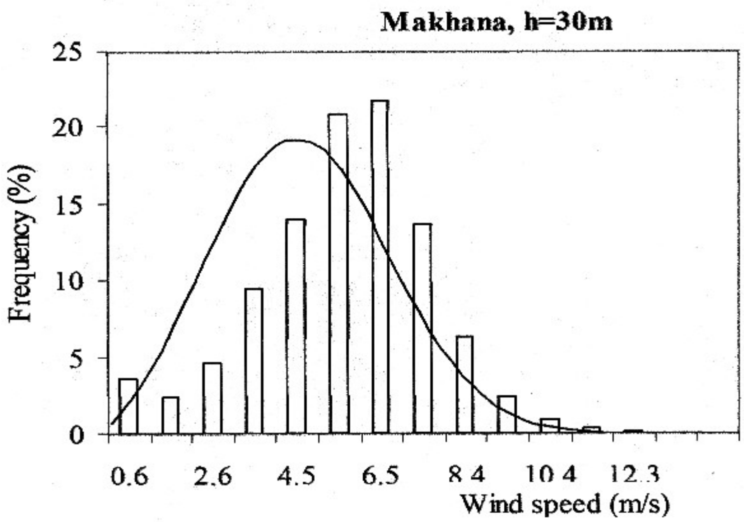

Fig. 9: Overall wind speed frequency and
wind speed frequency simulated by Weibull function

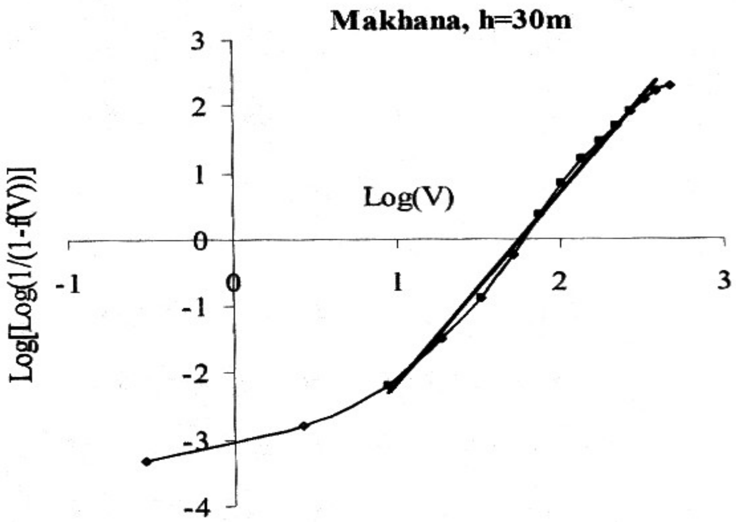

Fig. 10: Linear regression result of the wind data

Following the procedure of linear regression, an example of the obtained graph is given in Fig. 10, the two parameters of the Weibull distribution can be easily estimate using the wind speed data of the site. Table 2 summarizes the results for some sites as well the shear factor. The value of the shape factor, k, has been found to be slightly dependent on the station and on the height. The values of parameter scale, c, vary with the station and are near to the average wind speed. This happens because the Weibull distribution is a reasonable fit to the recorded data [19].

Table 2: Annual Weibull parameters and wind shear factor

Site	**Mboro 30 m**	**Mboro 15 m**	**Makhana 30 m**	**Makhana 15 m**	**Ndiandekhou 10 m**	**Pekesse 10 m**
k	2.027	1.926	2.838	2.662	2.249	1.697
c m/s)	3.987	3.817	5.811	5.031	2.974	2.342
α	0.159		0.556			

By considering a typical wind machine with cut-in speed (3 m/s) and rated speed (8 m/s), on the basis of the overall observed wind speed frequency (Fig. 11), it is possible to draw some preliminary conclusions in terms of wind quantifies in space.

At Pôtou, Ndiandekhou and Pekesse a wind turbine with the above specifications would be at a standstill for about 40 % and operate for about 60 % of the time at partial load.

At Mboro, more than 20 % of the wind speed was less than 3 m/s and about 70 % of the wind speeds recorded was between the cut-in and rated speed.

With such a high operating ratio, the overall wind speed in this region is strong enough to energize a simple mechanical wind pump nearly all the time indicating the feasibility of wind powered irrigation in this region, it can also be observed that the chances of wind speed high enough for wind-electric generation occurring at these sites are very limited and an aero-generator with 5 m/s cut-in would be standstill for a large period of the time.

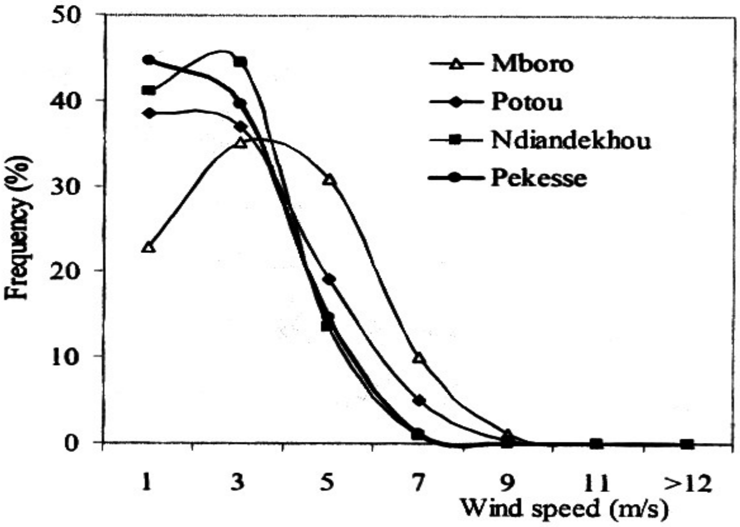

Fig. 11: Overall observed wind speed frequency for different sites

4.5 Energy extractable in the wind stream

The maximum fraction of the energy in the wind stream that can be extracted by a turbine rotor is given by Eq. 6. However wind machines are designed to operate within a certain wind speed range and it is not practical to extract all the energy from the wind stream over a given time interval.

Fig. 12 gives energy density produced from the wind during the month of July 1998 for Mboro and Pekesse at 10 m height. The maximum expected energy output occurs at speed between 5-6 m/s. The overall distribution of energy in the wind is shown in Fig. 13. Of note is the fact that the maximum of energy density occurs at a speed of 3.1 m/s at 30 m height which is close to the speed cut-in value of most of the typical wind machine. However this peak shifts for 10 m and 15 m heights to lower value of speed around 2 m/s.

5. CONCLUDING REMARKS

The use of wind energy in Senegal is too limited. The main goals of this study were to identify and understand wind characteristics at northern coastal locations of the country and to evaluate coastal potential for wind generation. An additional goal was an attempt to promote wind energy in Senegal and to bridge the gap in order to create prospective Senegalese Wind Atlas. These goals were accomplished. On completion of the study, the following observations can be drawn:

■ Overall the annual average wind speeds in northern coast region are moderate, based on data from the five locations. The average wind speed is 3.8 m/s and an annual energy of 158 kWh/m^2 could be extracted. The average wind speed is below the minimum speed, 6.0 m/s, needed for wind-electric generation, but wind powered water pumping applications appears to be a viable option. In addition, the demand of water for irrigation is seasonal and it is found that the windy season coincides with the dry season.

■ There is a distinct diurnal variation of the wind speed at ail sites, which attains above average conditions during the daylight hours, whilst dropping below average during the night.

■ A marked wind direction distribution is exhibited at all sites. Winds tend to blow from the sectors North-North-West to North-North-East with comparatively few days during which the winds blow from the remaining sectors.

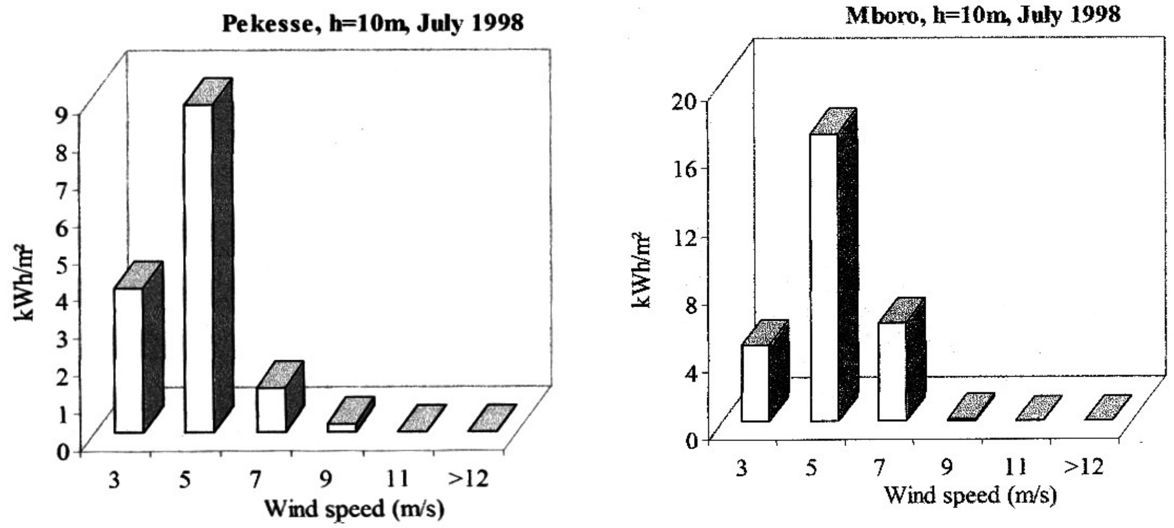

Fig. 12: Maximum energy density during July for the sites of Pekesse and Mboro

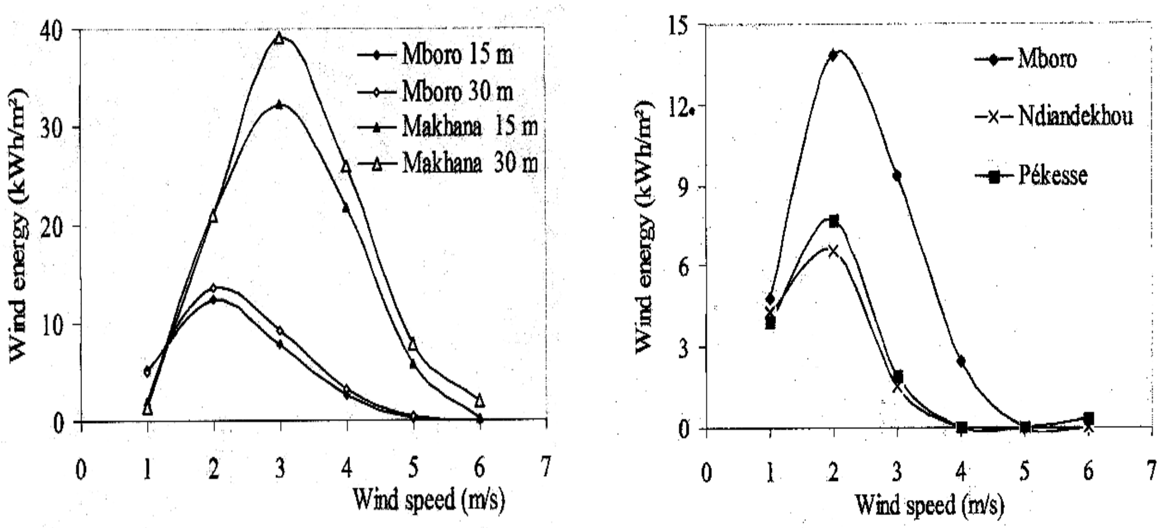

Fig. 13: Overall maximum energy density at different height for the different sites

■ The Weibull distribution is well suited for this particular area making it a handy tool for the calculation of parameters relevant to wind power generating systems.

■ Additional measurements may be considered for the region. However, the present work is only a preliminary study in order to estimate the wind energy potential at different locations. For a comprehensive study prior to construction and installing wind energy conversion systems, we should perform more detailed studies at each site separately.

■ Energy is essential to the economic and social development and will improve the quality of life in Senegal. More effort is needed to erect windmills for water pumping in rural areas with relative high wind potential. The result derived from this study encourages the utilization of wind energy on the coastal area.

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