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Analysis of wind distribution and potential wind energy in Senegal with a focus on Basse Casamance

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This work uses the Weibull distribution for assessing the wind potential in Senegal; a country located in West Africa. In this study, data from the ERA5 reanalysis and the Ziguinchor station were used to characterize the spatio-temporal variability of wind and its available power density at 10 m and 100 m of altitude. The results showed that the wind potential was stronger on the coast and the north-western part of the country. A case study was carried out in the Basse Casamance on five (5) different sites located on the coast and inland (Kafountine, Diembering, Kabrousse, Bignona, and Ziguinhor). The results show good wind potentials in the coastal areas: Kabrousse, Kafountine, and Diembering. The most favourable period for wind power production is the winter. The ERA5 data and those of the Ziguinchor weather station were also compared. The results showed that the annual average wind power density calculated with the ERA5 reanalysis was slightly higher than that of the data from the station. The wind rose's analysis, an essential parameter of the turbine's orientation, shows that the dominant wind direction in the Basse Casamance is northwest. In the last part of the study, an analysis of the choice of wind turbines adapted to the Ziguinchor site was carried out. Finally, this study provides the basic knowledge necessary for better planning of wind power projects in Senegal, especially in the Basse Casamance area.

Key words: Wind potential, power density, Weibull distribution, ERA5 reanalysis, Senegal.

INTRODUCTION

Climate change (also known as global warming) is one of the most significant challenges facing humanity. Numerous phenomena, such as rising sea levels, melting glaciers, and increasing ocean temperatures, indicate that the earth's average temperature increases (Fyrippis et al., 2010; Sagna et al., 2015). This process, called global warming, threatens the life of living things in many ways. Observations made since 1979 show that the temperature of the earth increases by 0.25°C per decade, and that of the seas rose by 0.13°C (Dia et al., 2009; Ghobadi et al., 2011; Ulu and Dombayci, 2018). Many studies have shown that the ongoing climate change is largely due to human activities especially the extensive use of fossil energy sources which lead to an increase in the concentration of greenhouse gases (such as carbon dioxide) in the atmosphere and then global warming

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(Fyrippis et al., 2010; Ghobadi et al., 2011; Sawadogo et al., 2019). One of the strategies recommended to mitigate this climate change is the use of renewable energies and among potential sources, the electrical energy from wind turbines because they do not emit greenhouse gases (Doutreloup et al., 2012; Tizpar et al., 2014).

Moreover, West African countries such as Senegal are struggling to meet the energy needs of their populations. In most of these countries, only 34% of people have access to electricity (Sawadogo et al, 2019). This is insufficient to satisfy the populations' energy needs, especially since energy constitutes the foundation of economic and social development, and access to it is a crucial issue in the fight against poverty. (Dia et al., 2009; Khan et al., 2018). Wind energy can be a solution for several uses (rural electrification, domestic use, industrial use, etc) (Bilal et al., 2010; Kidmo et al., 2015).

Although several projects and programs have been developed in recent years, the wind power sector remains underdeveloped in Senegal. For example, the currently operational installed capacity is 40 MW at the Taïba Ndiaye wind farm. This park is scheduled to reach an installed capacity of 158.7 MW by 2021 (https://www.taibaeolien.com/sn/projets/).

To address the energy needs of the population in a sustainable perspective, it would be vital to characterize and assess the wind energy potential in Senegal. The characterization of the spatial distribution and temporal evolution of wind speed properties and power densities are important factors to study using statistical tools applied to near-surface wind speed (10 m) and hub height 100 m (Abolude et al., 2020; Chen et al., 2018).

However, electricity generation from wind power is by its nature, intermittent (Doutreloup et al., 2012; Khan et al., 2018).

Accurate knowledge of the wind regime and the establishment of a wind atlas are prerequisites for the effective planning and implementation of wind projects (Kidmo et al., 2015). It is, therefore, necessary to have wind potential maps with high spatial and temporal resolution. These maps require measurements that take into account the spatial and temporal variability of wind (Fichaux, 2005; Tizpar et al., 2014; Fant et al., 2016; Sawadogo et al., 2019, 2020). Several wind potential assessment studies have been carried out on the north-western coastal axis of Senegal on specific sites, including Kayar and Potou for one year (Bilal et al, 2010). These studies highlight the existence of a wind potential favourable to the use of small wind turbines.

In particular, Bilal et al. (2010) show that the power density is greater on the Potou site than on the Kayar site. The wind potential on both sites is interesting for the exploitation of wind power by using wind turbines. However, none of these studies covered the whole country especially the Basse Casamance area (southern part of the country).

This work aimed at characterizing wind spatial and temporal distributions at 10 and 100 m and to assess the wind potential by analyzing its power density in Senegal with a focus on the Basse Casamance area.

MATERIALS AND METHODS

Description of the study area

Figure 1 shows the study area representing Senegal, which is the westernmost country in West Africa. Senegal's climate is of the Sudano-Sahelian type marked by the alternation of two distinct seasons: a dry season from November to June and a rainy season from July to October (Sagna et al., 2015). Rainfall generally decreases from south to north, with average annual values reaching 1200 mm in Ziguinchor (south of the country) and 220 mm in Podor (north of the country). The country's relief is flat and low except in the southern part of the country (Kedougou region) where there are elevations of up to 552 m above sea level. Also, Senegal's climate is characterized mainly by three types of wind: The maritime trade wind, coming from the Azores High which is from the NW; SE direction and the continental trade wind (also called the Harmattan) is a flow of warm, dry air carried by the Sahara-Libyan cell of N-E - S-W direction; this wind, which blows from November to May is responsible for the relatively high temperatures on the mainland and dust transport; the West African monsoon is a flow of warm, humid air from the anticyclone of St. Helena, located in the South Atlantic Ocean. The monsoon rages between April and October and is characterized, until the end of June, by a progressive extension of the rainfall from the coastal strip, located at about 5°N. The maximum of Coastal rains undergoes an abrupt movement up to 10°N called "the monsoon jump".

A total of 14 sites representing the capitals of the administrative regions of Senegal were selected to assess the annual and seasonal wind potentials of the country. A total of six (6) sites were considered in Basse Casamance (south-western part of the country) for the case study (Figure 1). The Latitudes and longitudes coordinates of these sites are summarised in Table 1.

Description of data

Wind resource assessment requires accurate wind measurements. Many published studies have used data from existing meteorological stations (Fichaux, 2005).

Due to the relatively high cost of setting up these meteorological stations, their spatial resolution remains coarse for wind applications. Besides, meteorological services are installed measurement stations in specific locations such as airports, ports, and densely populated areas. As a general rule, these locations are to be avoided when setting up wind farms. Wind resource assessment studies must use data from different sources because of these limitations, although *in situ* data from future wind farm sites are still the most reliable. Moreover, the choice of localities for wind farms is largely controlled by some physical (for example topography) and socioeconomic drivers (for example population density, transportation network, distance to water bodies, etc). For example, the topography may block or accelerate wind circulation.

Two datasets are mainly analyzed: the new ERA5 reanalysis of the European Centre for Medium-Range Weather Forecasts (ECMWF) and the *in situ* data from the meteorological station located at the University of Ziguinchor. The case study on Basse Casamance concerned six sites (Ziguinchor, Diembéring, Kabrousse, Kafountine, Bignona, and Oussouye).

ERA5 reanalyses were used in this work (Hersbach et al., 2019). Climate reanalyses combine past observations with model outputs

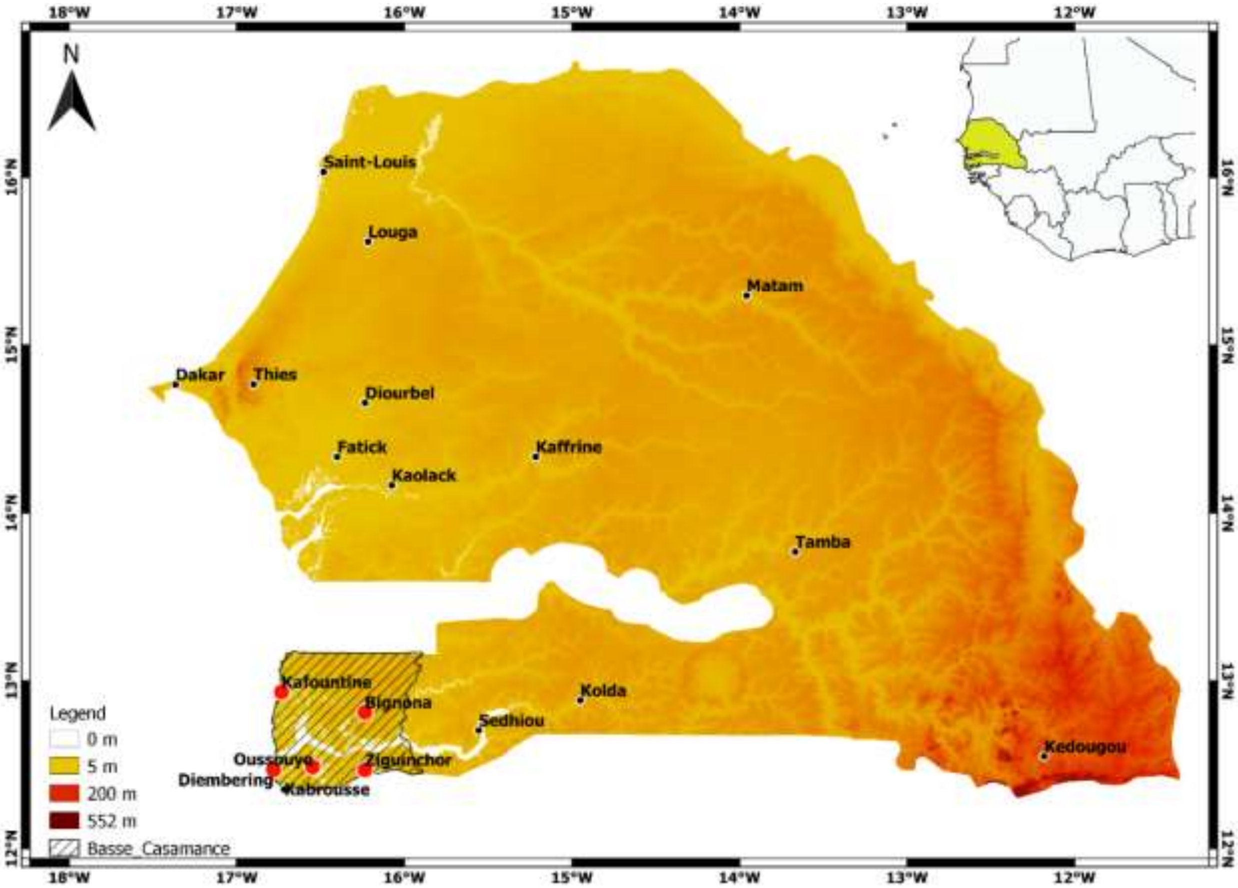

Figure 1. Map of the study area in Senegal with the different sites considered and with the altitude of the land in m.

Table 1. Locations (longitude, latitude, and altitude) of sites considered in this study.

Sites	Latitude °N	Longitude °W	Altitude (m)
Saint-Louis	16.0327	16.4816	03
Louga	15.6168	16.2166	32
Matam	15.2955	13.9579	36
Thies	14.7668	16.9000	65
Diourbel	14.6562	16.2345	12
Dakar	14.7646	17.3660	10
Kafrine	14.3345	15.2164	22
Fatick	14.3340	16.4011	06
Kaolack	14.1653	16.0757	10
Tamba	13.7690	16.6672	32
Ziguinchor	12.4696	16.2354	30
Sédhiou	12.7047	15.5562	25
Kolda	12.8835	14.9500	08
Kédougou	12.5501	12.1813	120
Kafountine	12.9333	16.7333	09
Bignona	12.8121	16.2354	09
Oussouye	12.4877	16.5470	14
Ziguinchor	12.4696	16.2354	30
Diembering	12.4693	16.7809	07
Kabrousse	12.3531	16.7172	04

Figure 2. Assane Seck University Weather Station (Ziguinchor, Senegal).

to generate consistent time series with multiple climate variables. Reanalyses are among the most used datasets in geophysical sciences especially in areas such as the Sahel (including Senegal) for which there are not many *in situ* measurements. They provide a complete description of the observed climate as it has evolved over the few decades on 3 D grids. Production of ERA5 started in early 2016 (Hersbach et al., 2019). During 2017 and 2018, segments of ERA5 were made publicly available in stages via the C3S Climate Data Store (CDS). The ERA5 reanalyses used in this work have a temporal resolution of 1 h and a high spatial resolution of 0.25° x 0.25° with atmospheric parameters available at 37 pressure levels. ERA5 is the latest version of climate reanalysis produced by the European Center for Medium-Range Weather Forecasting (ECMWF) providing hourly data for many atmospheric, land surface, and sea state parameters.

In situ data from the meteorological station (available over the 2016-2018 period) located on the site of the Assane Seck University of Ziguinchor (Figure 2) are used to assess the wind potential in this area but also as a comparison with the ERA5 reanalyses. The comparison was made on parameters such as the wind power density, Weibull parameters (k and c), wind turbulence index, and the wind rose at 10 m height.

Methods

Wind analysis (average speed, turbulence index, and wind occurrence) and the assessment of the associated parameters of the Weibull Wind Power Density (c and k) as well as the wind rose are necessary to better characterize the wind energy potential.

This work aimed at assessing the wind potential in Senegal by applying the distribution of Weibull.

More specifically, a statistical analysis of the wind was performed and its power density in Senegal with a focus on the Basse Casamance was calculated.

Two main datasets were analyzed: the new ERA5 reanalysis from the European Centre for Medium-Range Weather Forecasts (ECMWF) and the *in situ* data from the meteorological station located at the University of Ziguinchor. The case study on Basse Casamance concerned six sites (Ziguinchor, Diembéring, Kabrousse, Kafountine, Bignona, and Oussouye).

The wind speed data at 10 and 100 m are used to calculate some statistical parameters to better characterize the wind at different scales.

The power produced by the wind turbine is related to the wind speed (Doutreloup et al., 2012). The average wind in the time series of hourly data is determined by the expression (1) as used in some previous work (Coulombe, 2015; Didane et al., 2017):

$$\overline{V} = \frac{1}{n}\sum_{i=1}^{n} V_i \qquad (1)$$

Where, $\overline{V}$ and V_i are the average and instantaneous wind modulus speeds respectively.

The turbulence index I_t characterizes the degree of turbulence (turbulence intensity) of the wind. It influences the service life of the wind turbine through the fluctuations it induces on the turbine blades and rotor. The turbulence index is the ratio between the standard deviation σ and the average module of the wind speed $\overline{V}$. It is given by Equation 3 as used in Tizpar et al. (2014) and Madougou (2010):

$$I_t = \frac{\sigma}{\overline{v}} \qquad (2)$$

Where, σ is the standard deviation. This parameter measures the dispersion of the values around the mean. Also, it characterizes the turbulence global horizontal wind over the entire frequency range.

Its expression is given by equation (3) (Akinsanola et al., 2017;

Bassyouni et al., 2015):

$$\sigma(v) = \sqrt{\frac{1}{n}\sum_i (v_i - \bar{v})^2} \quad (3)$$

The Weibull distribution is the most used to calculate the frequency distribution of wind speed. The Weibull probability density function and the cumulative distribution are given by Equations 4 and 5 (Zhou et al., 2006; Akinsanola et al., 2017; Boudia and Guerri, 2015; Didane et al., 2017; Ghobadi et al., 2011).

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left(-\left(\frac{v}{c}\right)^k\right) \quad (4)$$

$$F(v) = 1 - \exp\left(-\left(\frac{v}{c}\right)^k\right) \quad (5)$$

The parameters c and k are the scale factor and the form factor, respectively. They are determined using Equations 6 and 7 (Madougou, 2010).

$$k = \left(\frac{\sigma}{\bar{v}}\right)^{-1.086} \quad (6)$$

The evaluation of wind power per unit area (density of wind power) is of fundamental importance for the evaluation of wind projects.

By knowing these two parameters (c and k), the power density of the wind can be given by the Equation (8) (Tizpar et al., 2014):

$$P = \frac{1}{2}.\rho.c^3.\Gamma\left(1 + \frac{3}{k}\right) \quad (8)$$

Where, P is the wind power density (W/m²) and ρ is the air density (kg/m^3) at the site.

Γ is the standard gamma function:

$$\Gamma(x) = \int_0^{+\infty} e^{-t}\, t^{x-1} dt \quad (9)$$

The energy produced by a wind turbine depends, among other things, on the wind speed, temperature, pressure, humidity, turbulence level, and characteristics of the wind turbine's power curve.

A key parameter called the capacity factor is generally used to select a suitable wind turbine for a site (Dunning et al., 2015). The wind turbine with the highest capacity factor represents the most suitable turbine for the site (Boudia and Guerri, 2015; Makhloufi and Kaabeche, 2019). Equation 10 gives the expression for calculating this parameter.

$$F_c = \frac{P_{moy}}{P_r} \quad (10)$$

F_c is the capacity factor (%), P_r is the rated power of the wind turbine (W) and P_{moy} is the average power at the output of the wind turbine given by expression in Equations 11 :

$$P_{moy} = \int_0^{+\infty} P_w\,.\,f(v).\,dv \quad (11)$$

P_w is the power at the output of the wind generator expressed by Equation 12. This power corresponds to the instantaneous speed (v) (Akinsanola et al., 2017).

$$P_w = \begin{cases} P_r.\left(\frac{v^k - {v_c}^k}{{v_r}^k - {v_c}^k}\right) & \text{if } v_c \le v \le v_r \\ P_r & \text{if } v_r \le v \le v_f \\ 0 & \text{if } v \le v_c \text{ or } v \ge v_f \end{cases} \quad (12)$$

v_c ,v_r, v_f represent the cut-in wind speed, rated wind speed, cut-out speed of the model wind turbine respectively and P_r is the rated electrical power,

The expressions 4, 9, and 11 give the average power (P_{moy}) at the output of the wind turbine (Equation 9):

$$P_{moy} = P_r.\left\{\frac{\exp\left[-\left(\frac{v_c}{c}\right)^k\right] - \exp\left[-\left(\frac{v_r}{c}\right)^k\right]}{\left(\frac{v_r}{c}\right)^k - \left(\frac{v_c}{c}\right)^k} - \exp\left[-\left(\frac{v_f}{c}\right)^k\right]\right\} \quad (13)$$

The energy E produced by a wind turbine per year can be calculated by multiplying the average power P_{moy} at the exit of the wind turbine by the number of hours in the year (Didane et al., 2017; Kwon, 2010):

$$E = P_{moy}.T \quad (14)$$

T represents the number of hours in the year.

Tables 2 and 3 represent the characteristics of some commercial and small power wind turbines available on the market. Their performances are evaluated on the Ziguinchor site at altitudes 100 m and 10 m using the ERA5 reanalysis and measurements data from the Ziguinchor station. In general, the best capacity factors correspond to wind turbines with the lowest cut-in and rated speeds. The wind turbine with the largest capacity factor represents the wind turbine best suited to the site (Dunning et al., 2015).

RESULTS AND DISCUSSION

Case study on Basse Casamance

The annual and seasonal averages of wind power densities were calculated for six sites in Ziguinchor region (Bignona, Diembering, Kabrousse, Kafountine, Oussouye and Ziguinchor) at 10 and 100 m altitude using the ERA5 reanalyses are shown in Figure 3. The results show that sites close to the coast (Diembering, Kabrousse and Kafountine) have a higher power density than those inland at 100 m. However, at 10 m, the inland station of Ziguinchor has a stronger wind potential than the coastal sites of Diembering and Kafountine.

As for the seasonal cycle, the highest wind power density values are found in the summer period at all sites at 10 m, except at Kabrousse and Ziguinchor where wind power density is higher in the spring. At 100 m, wind power is significantly high at all sites, especially those located on the coast. Lower energy production is generally observed during the winter season, regardless of the altitude. This may be due to the fact that during this period, the wind speed is low and fluctuates strongly, which is not conducive to good wind energy production.

Comparison between ERA5 reanalyses and *in situ* data at the Ziguinchor site

The scale parameter c is linked to the average wind speed, while the shape parameter k characterizes the wind behavior by following its values:

If k <1, there is a predominance of weak intensity winds;
If 1 < k < 2, there is a wind dispersion when considering

Table 2. Characteristics of some commercial wind turbines.

Turbine number	Type of wind turbine	$v_c\ (m.s^{-1})$	$v_r\ (m.s^{-1})$	$v_f\ (m.s^{-1})$	P_r (kW)
1	Vestas V-90	2.5	13	25	2000
2	SENVION MM92	3	12.5	24	2050
3	ENERCON E-82	2.5	11.5	28	2000
4	ENERCON E-70	2.5	13.5	34	2000
5	Nordex acciona N-90	3	12	25	2300
6	Vestas V-100	3.5	12	22	2000
7	Nordex acciona N-100	3	12	20	2500
8	SENVION MM82	3.5	14.5	25	2050
9	SIEMENS Gamesa G-90	3	14	25	2000
10	Vestas V-80	4	15	25	2000

Table 3. Characteristics of small power wind turbines (Bilal et al., 2010).

Turbine Number	Type of wind turbine	$v_c\ (m.s^{-1})$	$v_r\ (m.s^{-1})$	$v_f\ (m.s^{-1})$	P_r (W)
1	Eol/300W/12V	3.3	8	25	300
2	Eol/300W/12V	3.5	11	15	300
3	WS 400W/12W	3	12	17	400
4	Navitron200W/24V	3	7	25	200
5	Navitron300W/24V	3	8	25	300
6	WS 400W/24W	3	12	17	400
7	Eol/500W/24V	3.3	8	25	500
8	Eolsénégal/500W24V	3	7	10	500
9	Navitron500W/24V	3	8	25	500
10	HWG600/24V	3.5	12.5	17	600
11	Barney Inclin250W/48V	3	11	13	250
12	Barney Inclin600W/48V	3.5	11	13	600
13	Navitron/1000W/48V	3	12	25	1000
14	Barney Inclin1500W/48V	3.5	12	14	1500
15	Barney Inclin3000W/48V	3.5	12.5	14	3000
16	Barney Inclin6000W/48V	3.5	12	14	6000

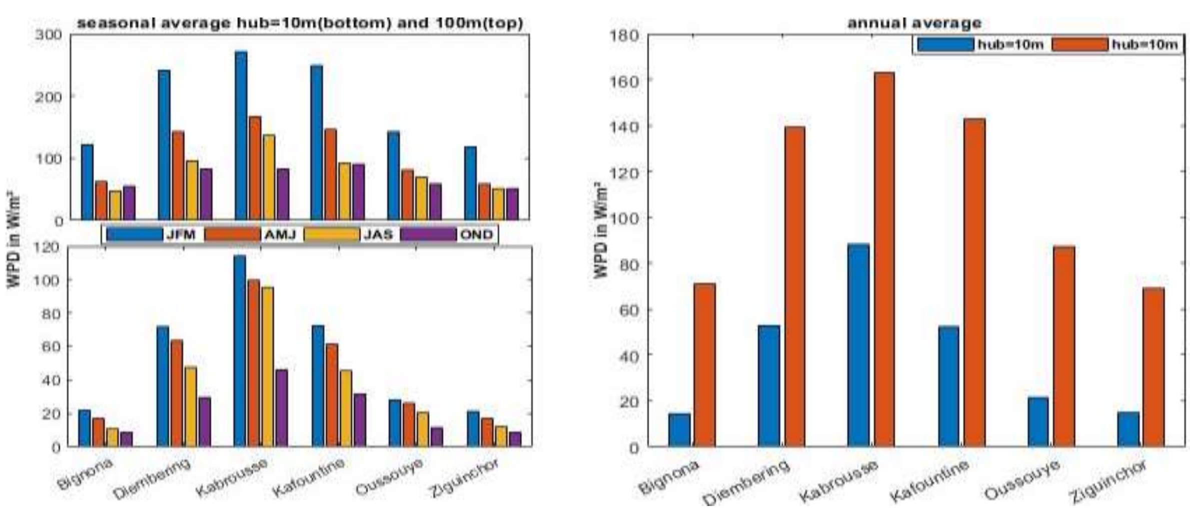

Figure 3. Annual and seasonal cycle average of wind power density at 10 m and 100 m in height at the Bignona, Diembering, Kabrousse, Kafountine, Oussouye and Ziguinchor sites averaged from 2014 to 2018 with ERA5 data in W/m^2.

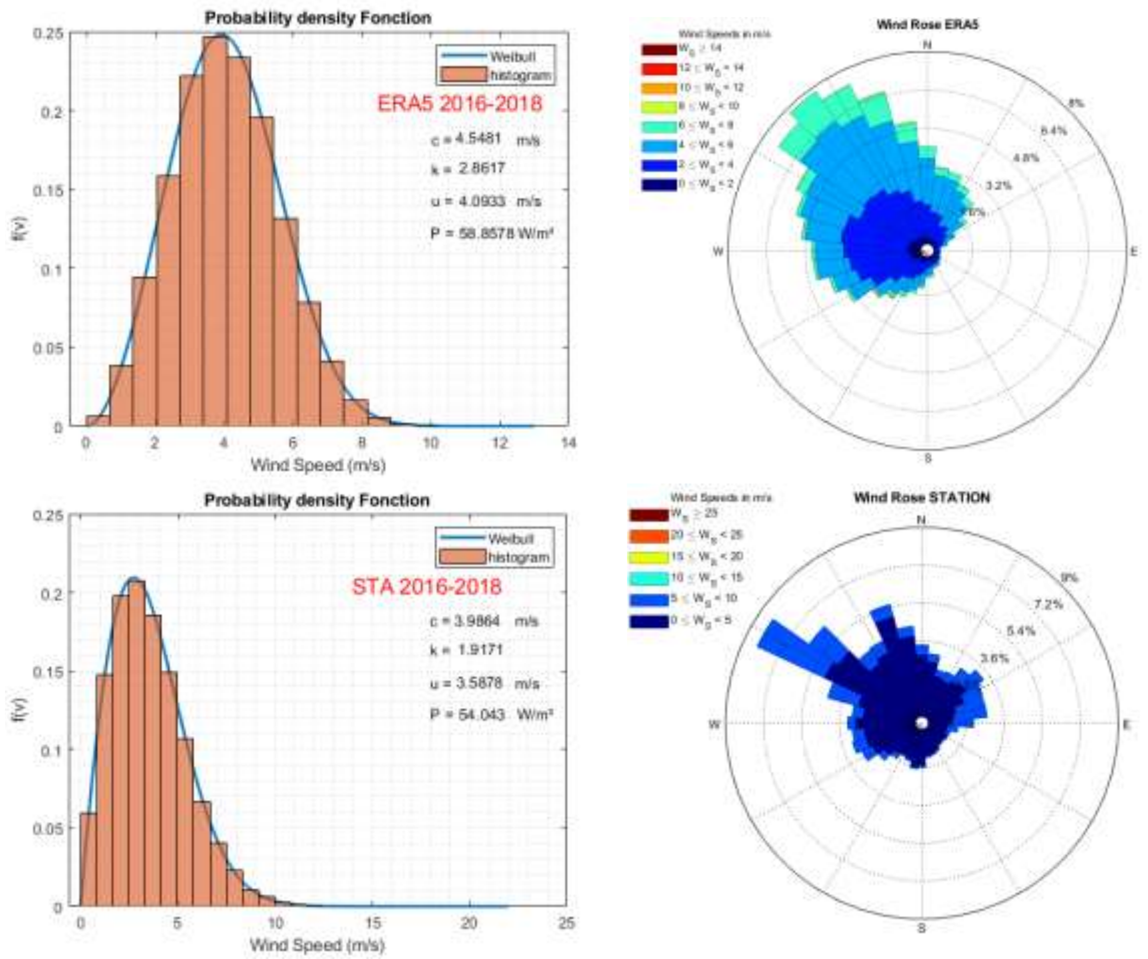

Figure 4. Probability density function and wind rose averaged from 2016 to 2018 at 10 m height with the ERA5 and Ziguinchor station data.

the direction; If k = 2, isotropic conditions exist; If k > 2, a privileged direction exists.

The annual wind power density and associated Weibull parameters calculated with ERA5 data are compared with those obtained with data from the Ziguinchor weather station for the period 2016 to 2018 at 10 m in height (Figure 4). The results show that the wind power density is higher in the case of ERA5 reanalyses (58.86 against 54.04 W/m^2). The Weibull parameters (k and c) obtained with ERA5 are slightly stronger than those of the weather station data. The average wind speed is higher for ERA5 reanalyses (4.09 m/s) compared to the weather station data (3.59 m/s).

The analysis of the form factor k shows that the wind is more regular in the case of ERA5 data (k = 2.86).

Another important parameter for assessing the wind potential in a particular area is the direction from which the wind blows by using the wind rose. The wind rose is the statistical distribution of the frequency of wind speeds over an area, for a given period, and by sector of direction (Fichaux, 2005). The wind rose and the probability density function shown in Figure 10 correspond to the ERA5 reanalyses and the Ziguinchor weather station for the 2016-2018 period. At first glance, the ERA5 data have a smoother wavy rose. Besides, they are grouped around a particular direction, compared to *in situ* data, which have a more irregular distribution.

The dominant wind direction for the ERA5 data comes from the NNW (North-North-West) sector and for the station from the WNW (West-North-West) sector. These directions correspond to the regime of trade winds, which blow relatively constantly, especially during the dry season in the country. Coming from the tropics (around 30 N-35 N), they blow from subtropical high-pressure regions to the equatorial low-pressure regions. The movement of Earth's rotation deflects trade winds westwards. Therefore, trade winds blow from northeast to southwest in the northern hemisphere (Veigas and Iglesias, 2012).

The seasonal cycle (summer, spring, fall, winter) of the wind directions obtained with the measurement data and the ERA5 reanalysis on the Ziguinchor site averaged over the period 2016 to 2018, is shown in Figure 5. The analysis shows that the dominant directions obtained with the measurement data and the ERA5 data are consistent. In summer, the preponderant direction is NNW (North-North-West) sector with both datasets.

In spring, there is a slight shift in wind direction towards the west. The prevailing wind directions come from the NW (North-West) sector with maximum frequencies of occurrence equal to 18 % and 14 %, respectively with station data and ERA5 reanalysis.

During the fall period, the WNW (West-North-West) sector predominates with measurement data and the west sector with the ERA5 reanalysis. A south-western component also appears probably due to the presence of the southern monsoon wind.

Several predominant directions are observed during the winter period, with both datasets traducing the wind direction dispersion. The strong NNW direction observed is associated with the installation of the Harmattan.

The last part of this section is involves the comparison of the associated Weibull parameters (k and c), the average wind speed, wind coefficient of variation and wind power density at 10 m altitude from the ERA5 reanalyses and the *in situ* data for the period 2016 to 2018 (Table 4).

The power density calculated with the ERA5 data is slightly stronger than that of the station. This result is consistent with the fact that the reanalysis product presents slightly stronger (lower) values of the wind speed (coefficient of variation). When considering the form factor, it is greater (lower) than values of k=2 with ERA5 reanalysis (station data), suggesting that the wind is more regular in the reanalysis data.

Choice of a wind turbine adapted to the Ziguinchor site

The average power output of the wind turbines, the corresponding capacity factor and the energy produced by the wind turbine are calculated for the ten most installed wind turbine types in the world (Table 2*).* The results are presented in Table 5. They show that the ENERCON E-82, Nordex acciona N-100 and Nordex acciona N-90 turbines have the highest capacity factors with 17.75, 15.14 and 15.14%, respectively. These wind turbines are, therefore, more suitable for the Ziguinchor site at 100 m. However, the average power output of the Nordex acciona N-100 is greater than that of the ENERCON E-82 and the Nordex acciona N-90. As a result, the Nordex acciona N-100 produces significantly more energy than the ENERCON E-82 and Nordex acciona N-90 with an equivalent output of 3.32 MWh/year compared to 3.11 MWh/year and 3.05 MWh/year, respectively.

The average power output of the wind turbines, the corresponding capacity factor, the average power, and the energy produced by the small turbines (Table 3) are calculated for each type of turbine.

The results obtained are presented in Table 6.

The results show that the EolSénégal / 500 W / 24 V and Navitron / 200 W / 24 V turbines have the highest capacity factors when considering the ERA5 data (22.53 and 22.54% respectively) and the *in situ* station data (21.17 and 22.47%, respectively). These wind turbines can operate over a long period of time producing the maximum of their rated power compared to others. They are therefore more suitable for the Ziguinchor site. However, the average output power of the EolSénégal wind turbine is stronger than that of Navitron. Also, the capacity factor obtained with the ERA5 data is smaller than that calculated with the weather station, except for the EolSénégal and Navitron turbines. Furthermore, the EolSénégal/500 W/24 V wind turbine produces much higher energy than Navitron/200 W/24 V for all data considered (987.5 KWh / year for ERA5 and 928.05 KWh / year for station data). These results show that the EolSénégal/500 W/24 V wind turbine is much better suited to the Ziguinchor site at 10 m.

Statistical analysis of Wind at 10 and 100 m in Senegal

This analysis used the ERA5 reanalysis at two altitudes (10 and 100 m). Data are averaged from 2014 to 2018. Average wind speed, wind turbulence index, and wind occurrence are calculated over four (4) periods of the year: winter (January-February-March: JFM), spring (April-May-June: AMJ), summer (July-August-September: JAS), and fall (October-November-December: OND).

Figure 6 shows the average wind speed. Its analysis shows stronger wind values more on the coast than inland with a peak in the north-western part of the study area. Also, a latitudinal distribution is found inland with weaker values in the south. The average speed is also higher at 100 m than at 10 m height, with a difference of 2 to 3 m/s. When considering the annual cycle, the wind is stronger during the winter and spring periods than during the summer and fall periods. This may be due to the fact that the country is under the influence of stronger north-easterly winds called Harmattan in winter and spring. Wind speeds are weaker in summer and fall, which are characterized by an unstable environment; the country is under the influence of the south-westerly flow called the monsoon flow and the Harmattan coming from the north. These results are consistent with those of Roy (1989). They have shown that the annual wind cycle in the lower layers of Senegal is marked by the presence of a trade wind in winter and spring. During this season, the wind speed increases regularly from October to December, reaching an average of 5 m/s. The wind speed stabilizes around this value from December to the first half of February. After a further increase in February

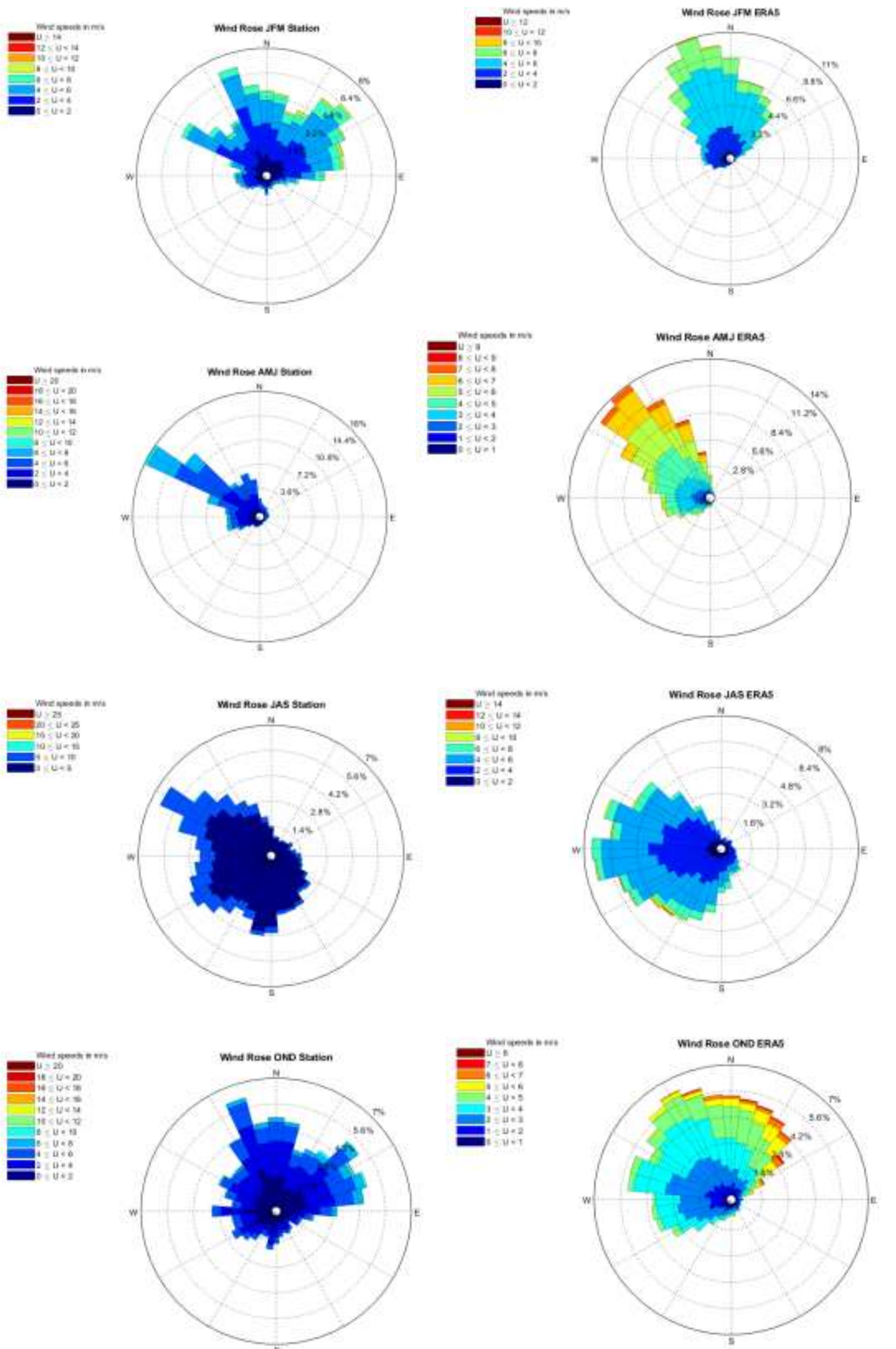

Figure 5. Seasonal wind direction cycle at the Ziguinchor site with ERA5 and the station data at 10 m height averaged from 2016 to 2018.

Table 4. Annual mean of the wind power density (P), the average wind speed (v), the coefficient of variation (CV), the form factor (k), the scale factor (c) for the weather station data and the ERA5 reanalysis averaged from 2016 to 2018 at 10 m.

Data	u (m/s)		CV		P (W/m^2)		k		c	
	ERA5	Station	ERA5	Station	ERA5	Station	ERA5	Station	ERA5	Station
Annual average	4.09	3 .59	0.38	0.54	58.86	54.04	2.86	1.92	4.55	3.99

Table 5. Capacity factor, average power and energy produced by the wind turbine at the Ziguinchor site with ERA5 data.

Turbine number	F_c %	P_{moy} (kW)	E(MWh/an)
1	12.92	258.38	2.27
2	13.60	278.88	2.44
3	17.75	354.90	3.11
4	11.71	234.12	2.05
5	15.14	348.16	3.05
6	14.19	283.85	2.49
7	15.14	378.44	3.32
8	8.59	176	1.54
9	10.10	201.92	1.77
10	7.18	143.68	1.26

Table 6. Capacity factor and average power for the Ziguinchor site.

	ERA5			Station		
Turbine number	F_c %	P_{moy} (W)	E(kWh/an)	F_c %	P_{moy} (W)	E(kWh/an)
1	14.33	43	377	15.33	46	403.28
2	5.17	15.52	136.07	7.36	22.08	193.55
3	4.68	18.73	164.2	7.28	29.11	255.2
4	22.54	45.07	395.14	21.47	42.94	376.37
5	15.46	46,39	406.67	16.69	50.06	438.89
6	4.68	18,73	164.19	7.28	29.11	255.2
7	14.33	71.67	628.27	15.33	76.67	672.13
8	22.53	112.65	987.5	21.17	105.87	928.05
9	15.46	77.32	677.78	16.69	83.44	731.49
10	3.55	21.28	186.52	5.62	33.70	295.46
11	6.04	15.1	132.36	8.7	21.75	190.7
12	5,17	31.04	272.14	7.35	44,12	386.78
13	4.68	46.83	410.48	7.28	72.78	638
14	4	60	525.84	6.12	91.8	804.61
15	3.55	106.39	932.61	5.62	168.48	1477
16	4	240	2103.4	6.12	367.15	3218.4

and March, maximum speeds are recorded during April.

In summer and autumn, from June to October, the trade winds give way to a variable and unstable wind regime; minimum speeds are observed during September. Furthermore, the conclusion on the seasonal cycle is supported by the work of Bilal et al. (2011), who found that on the Dakar-Saint-Louis axis, the dry season is characterized by strong wind regimes, while during the rainy season, the country is under the influence of a weaker wind.

Moreover, the contrasts observed between the coast and inland at 10 and 100 m altitudes may be due to

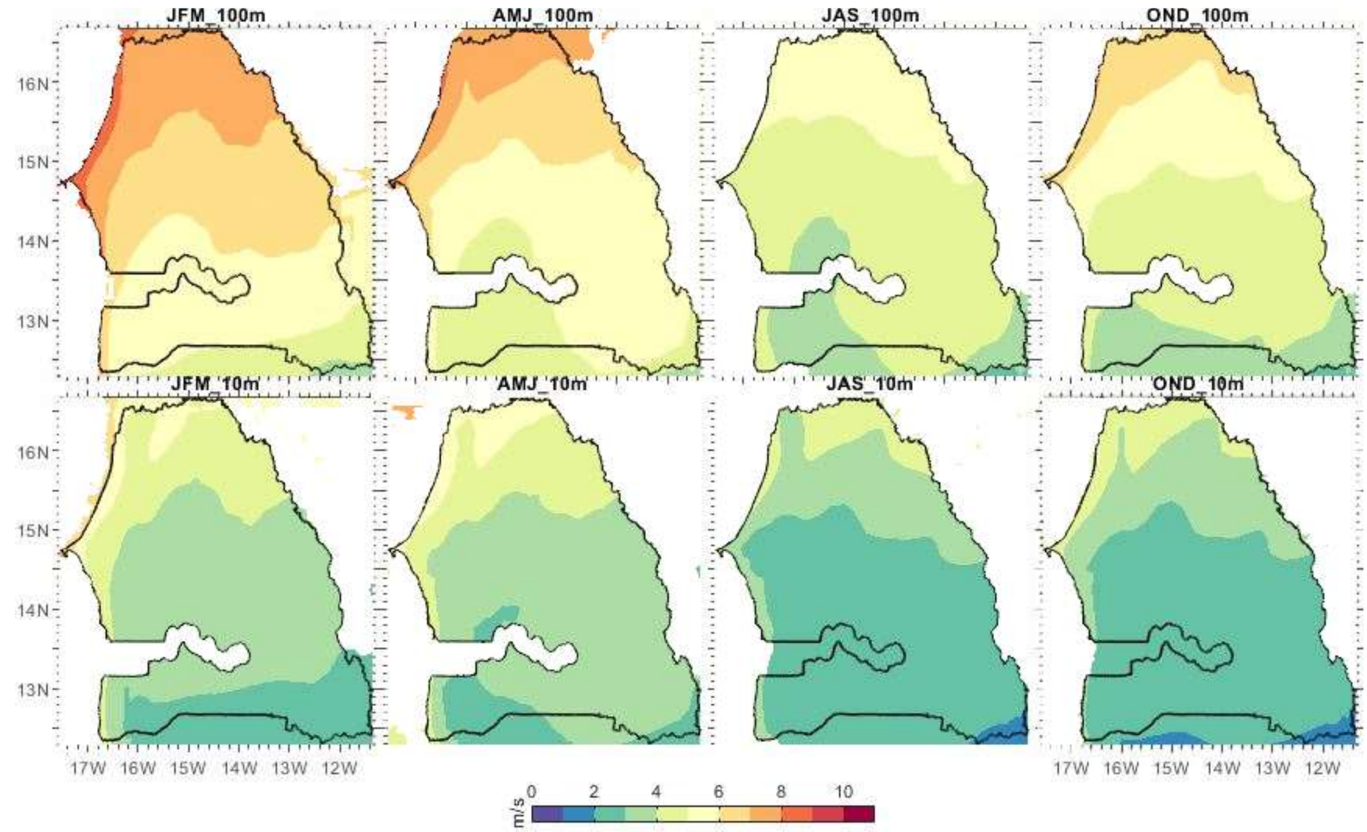

Figure 6. Seasonal cycle of the mean wind at 10 m and 100 m altitude in m/s averaged from 2014 to 2018.

friction (roughness effect), which is greater inland than on the coast but also closer to the land surface (10 m) than at higher altitude (100 m).

The presence of a regular wind favours the optimal production of wind turbines. The turbulence index is analyzed to characterize the regularity of the wind. Figure 7 shows the wind turbulence index on a seasonal time scale. This parameter is stronger during summer and fall periods than in the winter and spring at 10 and 100 m in height. Higher values are mainly observed in the south of the country, while the lowest values are located in the coastal areas and the northern part.

The weakness of the turbulence index in winter and spring associated with a stronger wind intensity is a sign that these two periods will have good wind potentials which will facilitate good electricity production.

The seasonal cycle of the occurrence of wind classes is illustrated in Figure 8. Wind occurrence is the percentage of time the same wind class is observed. Wind class analysis allows choosing a suitable turbine for a site. We have defined two wind classes. The first class corresponds to wind speeds between 0 and 5 m/s, and the second those higher than 5 m/s. The 5 m/s threshold corresponds to the starting (or cut-in) speed of commercial wind turbines (Doutreloup et al., 2012).

The analysis of class 1 at 100 m in height shows that speeds between 0 and 5 are almost absent in the study area during the winter, spring, and fall periods (< 10%). However, this wind class is omnipresent in Senegal during the summer, with values reaching 90% in the south-east of the country. When considering the altitude of 10 m, a strong occurrence of this class is found at 10 m altitude over the entire country, especially in the center and south in winter, spring and fall. Concerning class 2, the highest occurrence (70%) is found in the central and northern part of the domain, while it is almost absent in the summer.

Analysis of wind potential density

Figure 9 shows the annual average wind power density calculated over the senegalese territory from 2014 to 2018. The wind potential is higher at 100 m and on the coastal part.

Inland and at an altitude of 10 m, the wind power density does not exceed 50 W/m^2 from the south to the center of the domain. Wind power density values > 50 W/m^2 are found in the northern part of the domain especially in the extreme northwest where it is greater than or equal to 100 W/m^2. As for the wind power density at 100 m in height, a north-south gradient is observed

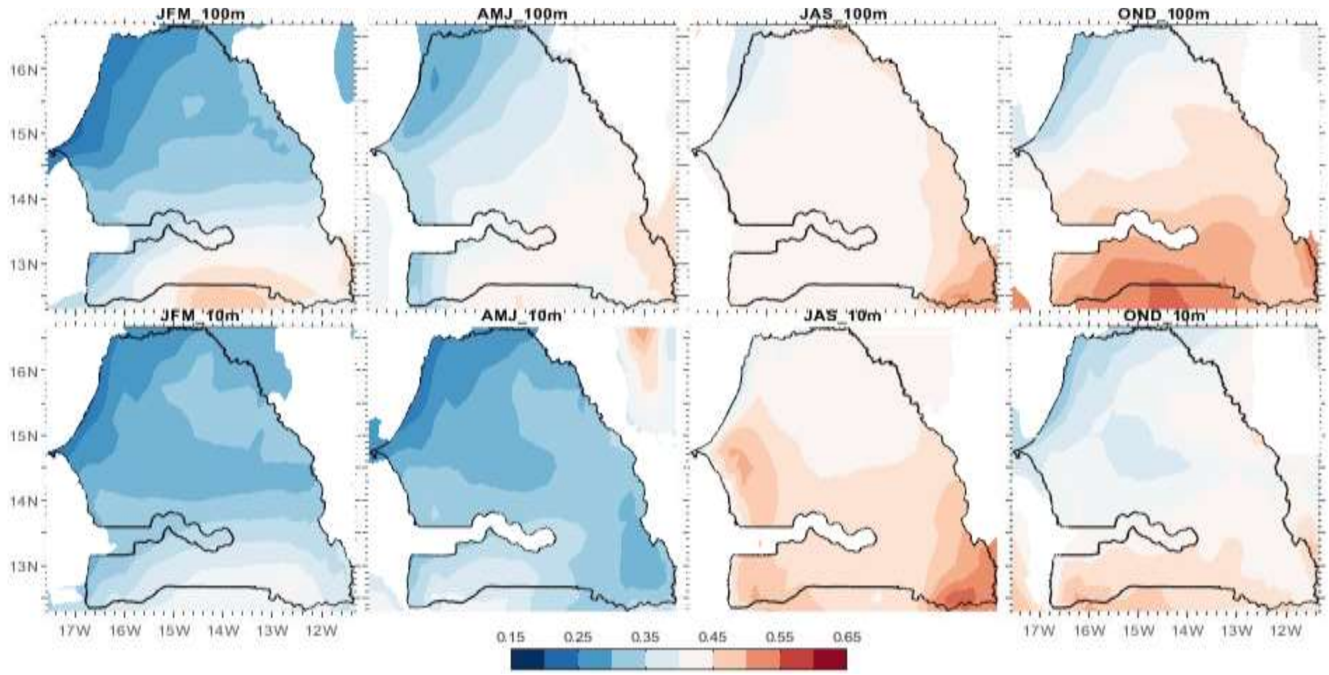

Figure 7. Seasonal cycle of the wind turbulence index at 10 m and 100 m altitude averaged from 2014 to 2018.

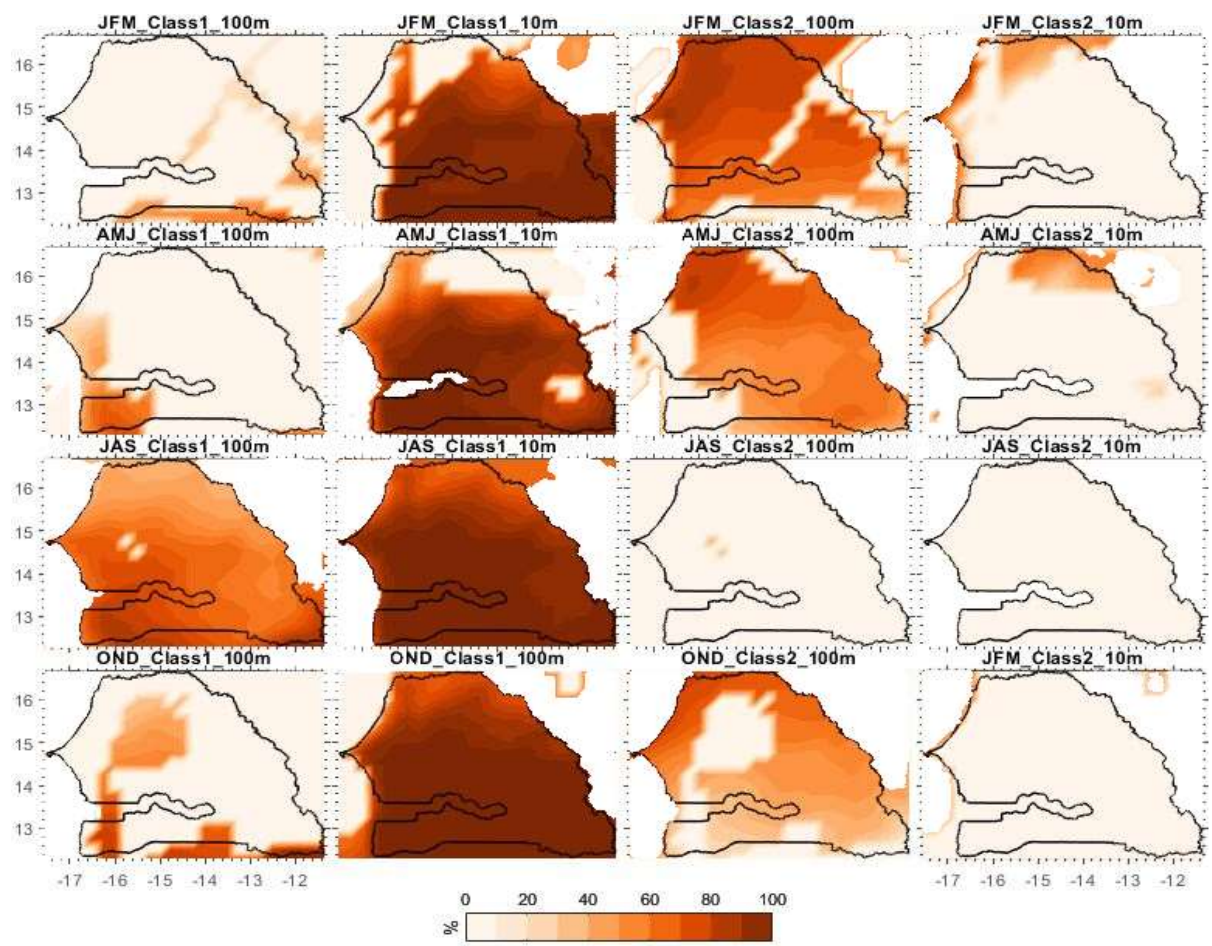

Figure 8. Seasonal cycle of wind occurrence in (%) averaged from 2014 to 2018 at 10 and 100 m.

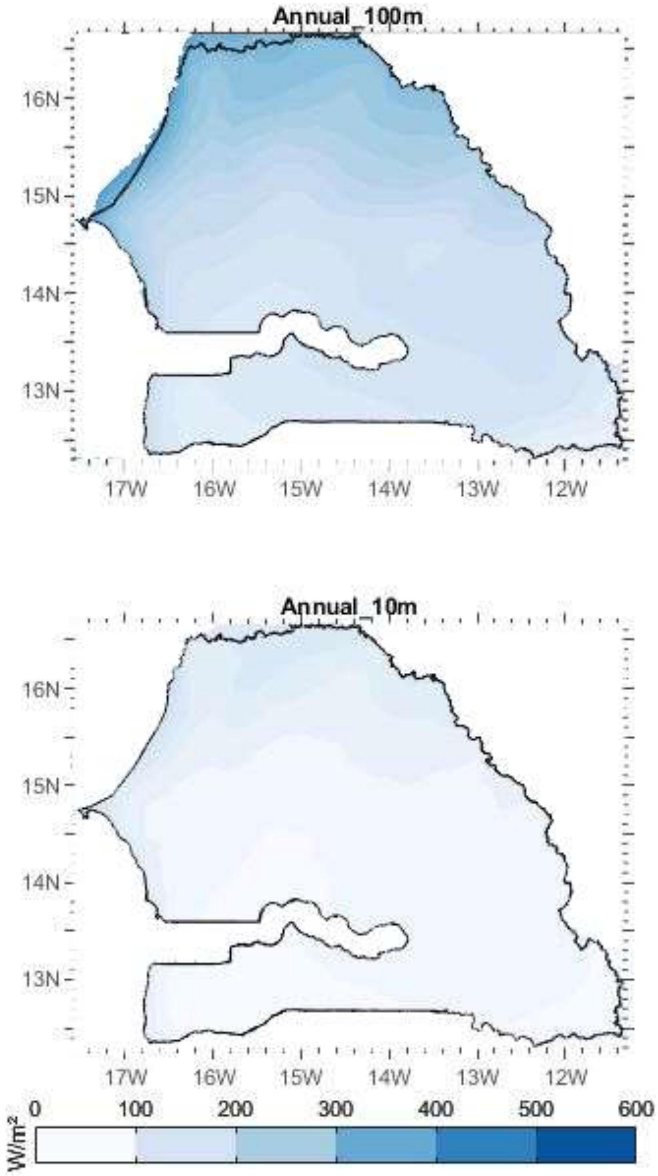

Figure 9. Annual wind power density from 2014 to 2016 at 10 m and 100 m altitude (W/m^2).

over the country with a maximum (minimum) potential energy in the north (south). Values inferior to 100 W/m^2 are recorded on the south-eastern part of the domain (between 11 °N and 12 °N). In the center of the country, the energy power density varies between 100 and 200 W/m^2 are recorded. Also, wind power density values ranging between 200 W/m^2 and 300 W/m^2 are recorded in the northern part of the domain (between 15 °N and 18 °N). The highest values are located in the north-western part of the country (> 300 W/m^2).

Wind power density is calculated in Senegal during spring, summer, fall, and winter for the period 2014-2018 (Figure 10*).* It was found that for all the seasons, the wind power density was higher at 100 m than at an altitude of 10 m. The winter and spring periods are more favourable in terms of wind energy production for both altitudes. Inland and at an altitude of 10 m, the wind power density does not exceed 100 W/m^2, except in the northern part in winter and the northwest in spring, where a wind power density between 100 and 200 W/m² in spring, is observed. On the coast, on the Dakar / Saint-Louis axis (from 13 °N to 18 °N), the wind power density reaches values ranging between 100 and 200 W/m^2.

At an altitude of 100 m, values below 100 W/m^2 are recorded in winter and spring on the southern part of the domain (12 °N and 13 °N) and in the center-south (12 °N - 15 °N) in summer. As for the winter and spring periods, values greater than 300 W/m^2 are recorded in the north-western part of the country.

The annual average wind power density at 10 m and 100 m of altitude at 14 sites (cities representing the capitals of administrative regions of Senegal) averaged over the 2014-2018 period is presented in Figure 11. The analysis shows that the maximum wind power density is diagnosed in the north-west coast of the Dakar site (355 W/m^2 at 100 m and 153 W/m^2 at 10 m), followed by Saint-Louis 350 W/m² and 137 W/m² at 100 and 10 m respectively).

At 100 m, strong values are also found at the Louga (210 W/m^2), Thiès (202 W/m^2), and Matam (194 W/m^2) sites located respectively in the center, western and north-eastern parts of the country.

The lowest power density is recorded in the south of Senegal with minimum values of 95 W/m^2 and 65 W/m^2 obtained in Kolda and Kedougou respectively. Generally, sites located in the southern part of the country have a low wind power density suggesting that their geography may play a particular role. Indeed, the southern part of the country has a stronger vegetation cover, which may reduce the surface wind field through friction effects.

Conclusion

This work analyses the spatio-temporal variability of wind at the altitudes of 10 m and 100 m and assesses the wind energy potential in Senegal, focusing on the Basse Casamance.

The results show that the wind is more intense in the coastal zone, particularly the north-western part (Dakar/Saint-Louis axis). Moreover, the wind is higher during the winter and spring seasons than in the fall and summer periods at the seasonal scale. During summer (rainy season in Senegal) and fall (transition period between the rainy season and the dry season) periods, the turbulence index is higher, especially in the southern part of Senegal.

Wind occurrence has also been calculated for two wind categories at 10 m and 100 m. The results showed that class 2 (wind speeds inferior to 5 m/s) is more preponderant at 100 m. Class 1 (wind speeds superior to 5 m/s) remains significant inland and south of 15 °N at

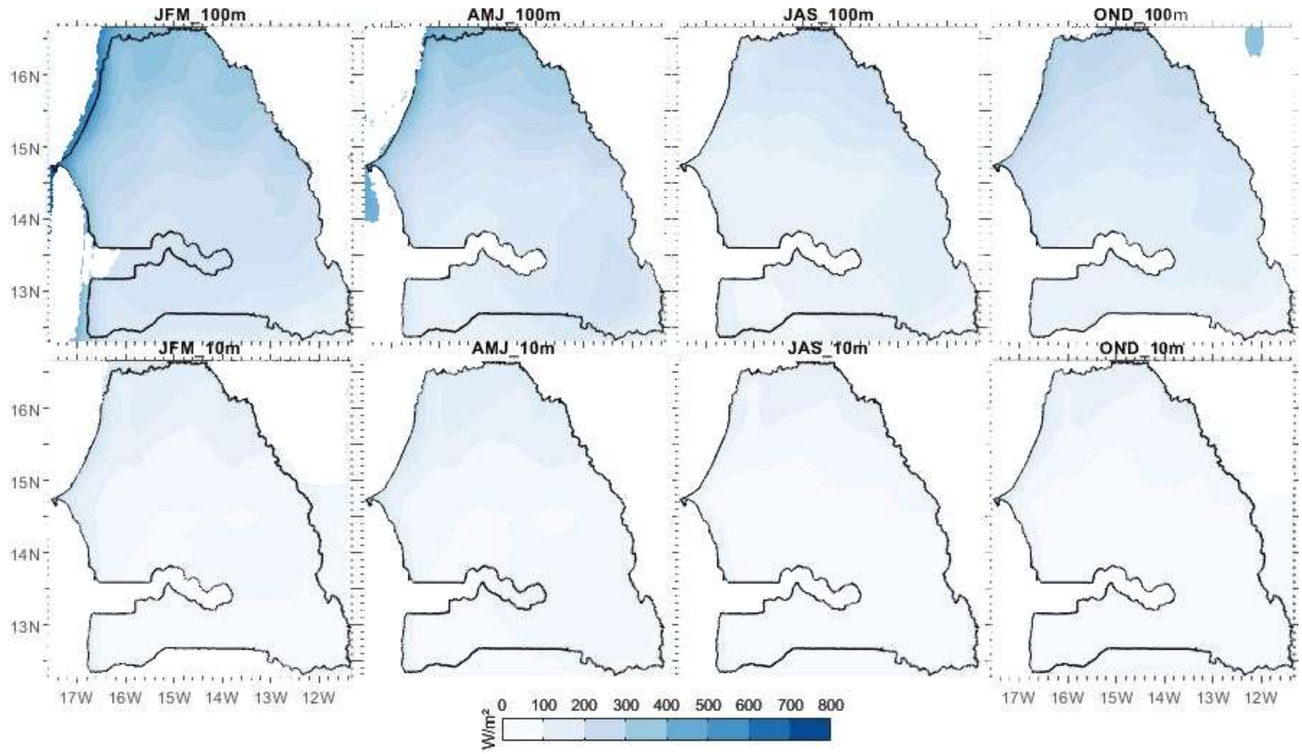

Figure 10. Seasonal cycle of wind power density from 2014 to 2016 at 10m and 100 m of altitude in W/m^2.

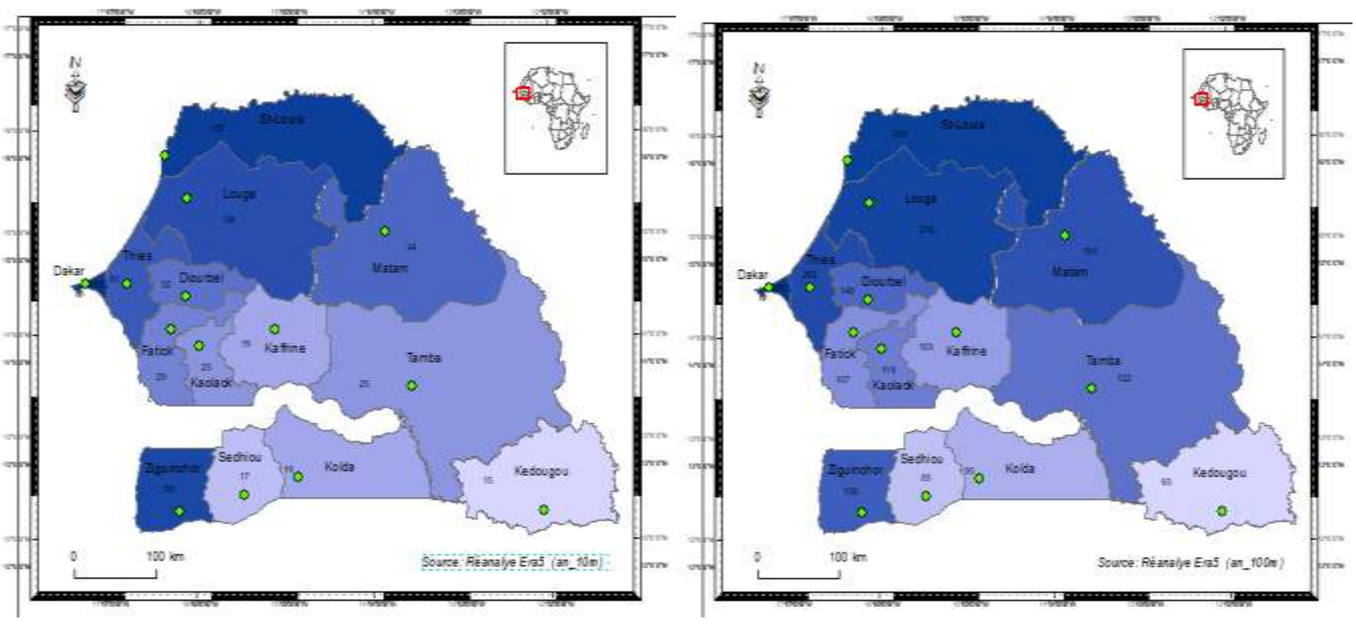

Figure 11. Annual mean Wind power density in 14 cities of Senegal at 10 m (left) and 100 m (right) averaged from 2014 to 2018. The unit is in W/m^2.

10 and 100 m.

The wind power density at annual and seasonal scales has been calculated in Senegal at 10 m and 100 m. Wind power densities are stronger at sites near the coast and in the northern part of Senegal.

A case study was carried out on six (6) sites (Diembering, Kabrousse, Kafoutine, Oussouye, Bignona, and Ziguinchor) in the Basse Casamance. This analysis revealed that the wind power density at sites close to the coast (Diembering, Kabrousse, and Kafoutine) is higher at 100 m.

The data from ERA5 have been compared with those from the Ziguinchor station at 10 m over the 2016-2018 period. The average speed (v) and power density (P) obtained with ERA5 data are slightly stronger than those obtained with the in situ data.

The wind rose analysis shows that the ERA5 reanalyses and the data from the Ziguinchor weather station give concordant results. Thus, in spring, which is the most favourable season for electricity production, the dominant wind direction is West-North-West.

Finally, an analysis of the most suitable wind turbines at the Ziguinchor site shows that Nordex acciona N-100 and EolSénégal/500 W/24 V wind turbines are more suitable for this site, at 100 m and 10 m respectively.

This study will provide the knowledge necessary for the choice of implantation of future wind energy projects for companies evolving in the field and some tools to political decision-makers.

In perspective, a technical and economic analysis study of a wind system intended for the production of electricity for Ziguinchor and a few other sites in Basse Casamance would be interesting. It would also be important to study the impact of global warming at 1.5 and 2°C on the wind power density in Senegal.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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