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Investigation on offshore wind energy potential in Benin Republic

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Abstract

This article presents a study on offshore wind energy viability in Benin Republic. Weibull law has been used to model the spatial distribution of daily wind speed data in Benin Republic's Exclusive Economic Zone. The spatial distribution of wind energy potential in Benin's exclusive economic zone has been obtained at several heights by extrapolating Weibull parameters. Wind resource has then been categorized using National Renewable Energy Laboratory standards. Bathymetric data in the exclusive economic zone are used to determine areas showing good compromise between exploitable wind potential and turbine's foundation. We have shown that Benin's offshore resources can reach Class 7 at 100 m height, Class 6, respectively, at 100 and 80 m heights and finally Class 5 at 50 m height. We have also shown that locations close to the shore are the most suitable to offshore wind power generation in Benin's exclusive economic zone.

Keywords

Offshore wind energy, exclusive economic zone, Weibull law, bathymetric data

Introduction

Wind energy is one of the top promising renewable energy sources in the world. According to the World Energy Council (WEC) report in 2015, wind energy contribution in the global energy mix was 7% in 2015 (WEC, 2016). Wind energy farms can mainly be installed onshore or offshore.

Offshore wind farms are interesting because they include stable and better wind resources than onshore wind farms, they have less environmental impact and fewer constraints on wind turbine dimensions, and the fuel cost is zero (Blanco, 2009; Colmenar-Santos et al., 2016; Hong and Möller, 2011). On the contrary, wind farm development requires substantial investments (Blanco, 2009; Dicorato et al., 2011). It is therefore important to conduct preliminary studies in order to assess the viability of any offshore wind project.

From the literature review, the first step in offshore wind power projects studies is to evaluate the viability of wind energy potential for power generation. Then further studies focuses on the analysis of techno-economic feasibility of the project. A techno-economic assessment of offshore wind energy has been conducted in Chile (Mattar and Guzmán-Ibarra, 2017). The capacity factor and performances of the V164-8.0 MW turbine was determined as well as economic indicators for the profitability. The study highlighted the areas favorable for offshore generation in Chile. Another research assessed offshore wind energy resource of the Persian Gulf, considering uncertainty method (Amirinia et al., 2017). This study combined a Monte-Carlo simulation with geographical information

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system (GIS) to analyze the techno-economic feasibility of offshore wind energy in the Persian Gulf. Oh et al. described a three-step methodology for assessing electricity production and value for offshore environment resource (Dhanju et al., 2008). The first step of this methodology consisted on finding the so-called "exclusion zone." Next, the location and number of wind turbines was determined, leading to the calculation of expected electricity production.

The next step is related to economic aspect of the project. Other studies have been conducted in Korea assessing offshore energy potential (Oh et al., 2012) and determining the optimal location for an offshore wind farm (Kim et al., 2013). Some other studies assessed offshore wind energy potential in China under several constrains (Hong and Möller, 2011), and studied China's offshore wind target by 2020 (Hong and Möller, 2012). Nagababu et al. presented a GIS-based methodology to characterize offshore wind power potential in Western and Eastern coasts of India under technical, economical, and marine ecosystem considerations (Nagababu et al., 2017). Regarding Africa in general, it is worth reporting a research presented by Mentis et al. (2015) assessing technical onshore wind energy potential in Africa using a GIS-based approach.

From the literature review, there is no known research published investigating offshore wind energy potential in Benin Republic. One reason is that there is no data measurement available from local metrological offices. Therefore, satellite data can be used instead as done in many previous studies (Amirinia et al., 2017; Hong and Möller, 2011; Mattar and Guzmán-Ibarra, 2017; Mentis et al., 2015; Soukissian et al., 2017).

The aim of this research is to answer the question: Is there any exploitable offshore wind energy potential in Benin Republic for power generation?

In this article, section "Offshore wind resource assessment" presents the study area and details about the data used. Then section "Results and discussion" presents the modeling methodology of offshore wind resource. Section "Discussion" presents the results and discussion followed by the conclusion of the article.

Offshore wind resource assessment

Offshore wind energy assessment is done following the procedure presented at Figure 1.

Wind distribution modeling

In wind energy, wind speed distribution is often modeled using probability density functions. The most common function used through the published papers is the Weibull function f(v) defined as (Adaramola et al., 2015; Allouhi et al., 2017; Amirinia et al., 2017; Awanou et al., 1991; Chang et al., 2003; Mattar and Guzmán-Ibarra, 2017; Mirhosseini et al., 2011; Mohammed et al., 2013; Oh et al., 2012; Oyedepo et al., 2012; Tolessa, 2013)

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

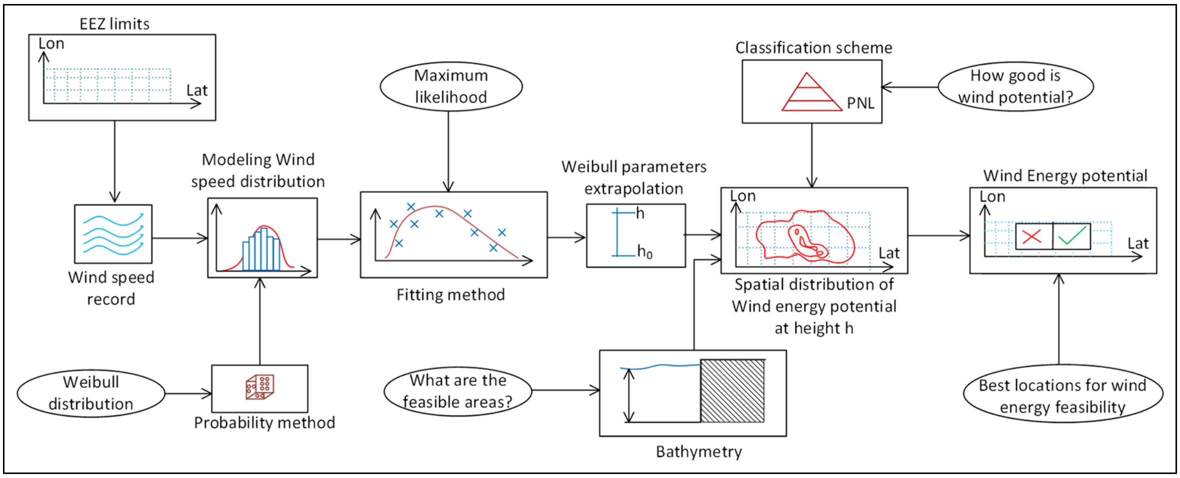

Figure 1. Methodology for wind energy potential investigation.

where k is the dimensionless Weibull shape parameter, c is Weibull scale parameter (m/s), v is coordinate dependent wind speed, and f(v) is the probability of observing the wind speed v. The Weibull parameters c and k are generally calculated using the following:

The Weibull probability plotting paper method (Takle and Brown, 1978);

The moment method (Seguro and Lambert, 2000; Vela, 2009);

The maximum likelihood method (Seguro and Lambert, 2000; Vela, 2009);

The energy pattern factor method (Seguro and Lambert, 2000; Vela, 2009).

In this article, the maximum likelihood method is used since it is the most recommended method for fitting a Weibull distribution in wind energy analysis (Seguro and Lambert, 2000). The likelihood function L_v is

$$L_v = \prod_{i=1}^{N} f(V_i) = \prod_{i=1}^{N} \left(\frac{k}{c}\right) \cdot \left(\frac{V_i}{c}\right)^{k-1} \cdot \exp\left(-\left(\frac{V_i}{c}\right)^{k}\right) \tag{2}$$

The maximum likelihood consists in the maximization of $\ln(L_v)$ given by

$$\ln(L_v) = \sum_{i=1}^{N} \ln k - k\sum_{i=1}^{N} \ln c + (k-1)\sum_{i=1}^{N} \ln V_i - \sum_{i=1}^{N} \left(\frac{V_i}{c}\right)^{k} \tag{3}$$

$\ln(L_v)$ is maximal if

$$\begin{cases} \dfrac{\partial \ln(L_v)}{\partial k} = 0 \\ \dfrac{\partial \ln(L_v)}{\partial c} = 0 \end{cases} \tag{4}$$

The solution of this system leads to the set on non-linear equations

$$\begin{cases} \sum_{i=1}^{N} \left\{ \frac{1}{k} + \left[1 - \left(\frac{v_i}{c}\right)^{k}\right] \cdot \ln\left(\frac{v_i}{c}\right) \right\} = 0 \\ \sum_{i=1}^{N} \left(\frac{k}{c}\right) \cdot \left[-1 + \left(\frac{v_i}{c}\right)^{k}\right] = 0 \end{cases} \tag{5}$$

where v_i represents the value of the wind speed at time i, and N is the total number of wind speed data. The equation (5) is solved using iterative techniques (Nedaei et al., 2014; Seguro and Lambert, 2000; Vela, 2009).

Weibull parameters extrapolation and power density

Because wind turbines are installed at heights greater than 10 m, it is important to investigate on wind potential at higher heights. One of the advantages of using Weibull distribution is that Weibull parameters can be obtained at a height different from measurement height. This extrapolation approach developed by Justus and Mikhail (1976) was subject to comparison with wind records data extrapolation approach in Gualtieri and Secci (2012). This study demonstrated the extrapolation of Weibull wind speed distribution to be a clear advantage in wind energy studies versus extrapolating hourly wind records (Gualtieri and Secci, 2012). The Weibull parameters at height h is given by (Adaramola et al., 2015; Justus et al., 1978; Justus and Mikhail, 1976)

$$c(h) = c_0 \cdot \left(\frac{h}{h_0}\right)^{n} \tag{6}$$

$$k(h) = k_0 \cdot \frac{1 - 0.088 \ln\left(\frac{h_0}{10}\right)}{1 - 0.088 \ln\left(\frac{h}{10}\right)} \tag{7}$$

where c_0 and k_0, respectively, represent Weibull scale parameter and shape parameter at height h; h_0 is reference height; and n is an exponent defined as (Adaramola et al., 2015)

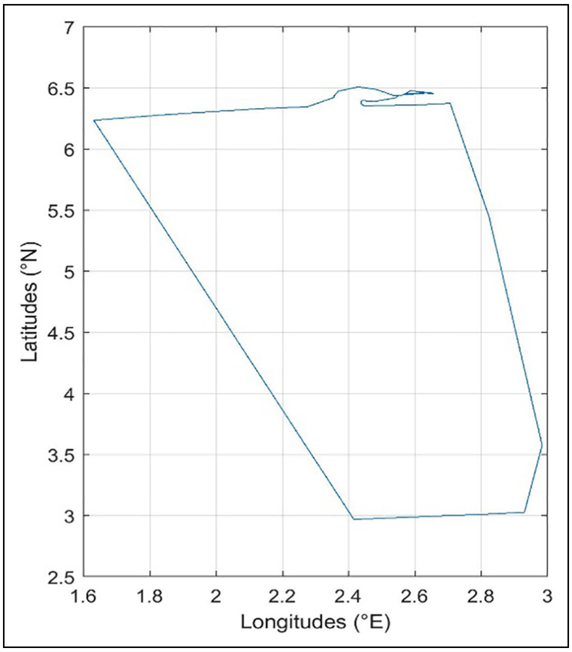

Figure 2. Benin Republic's Exclusive Economic Zone visualization.

$$n = \frac{0.37 - 0.088\ln(C_0)}{1 - 0.088\ln\left(\frac{h}{10}\right)} \tag{8}$$

Wind power density can then be computed using Weibull probability density function by

$$P(v(h)) = \frac{1}{2}\cdot \rho \cdot c(h)^3 \cdot \Gamma\left(\frac{k(h)+3}{k(h)}\right) \tag{9}$$

where Γ is the gamma function defined as $\Gamma(x) = \int_0^\infty t^{(x-1)} \cdot \exp(-t)dt$, and ρ is the air density at the site in kg/m^3.

It is important to point out that all the parameters presented in this section are location dependent since wind speed has a spatial variability.

Results and discussion

Study area and data

Study area. This article focuses on offshore wind resources in Benin Republic. In fact, Benin Republic ratified United Nations Convention on the Law of the Sea of 10 December 1982 in October 1997 (United Nations, n.d.). According to this law, each country has special rights regarding the exploration and use of marine resources, including energy production from water and wind in a certain zone (Unclos and Agreement on Part XI—Preamble and frame index, n.d.). This zone is called Exclusive Economic Zone (EEZ). The EEZ delimitation of Benin Republic is presented in Figure 2. According to the information presented by Flanders Marine Institute (2018), the total area of Benin's EEZ is roughly 35,528.369 km^2 and is bounded from longitude 1.63°E–2.97°E and from latitude 2.98°N–6.51°N. For the rest of this article, we only focus on data contained within these boundaries.

Wind speed data. Wind speed database is obtained from the US National Oceanic and Atmospheric Administration (NOOA) website (NOOA, n.d.). One Mission of this organization is to understand and predict changes in climate, weather, oceans, and coasts. In order to accomplish this mission, many weather parameters are measured via satellite observation. Among these are offshore wind speed data. This data consist of spatio-temporal distribution of wind speed measured at 10 m in 2013 at 0.25° by 0.25°grid resolution. A visualization of

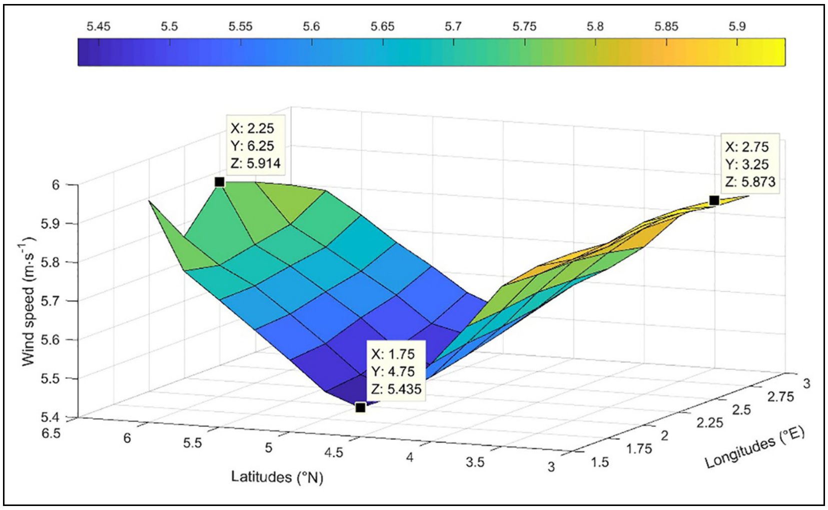

Figure 3. Spatial distribution of wind speed in Benin's EEZ measured at 10 m in 2013.

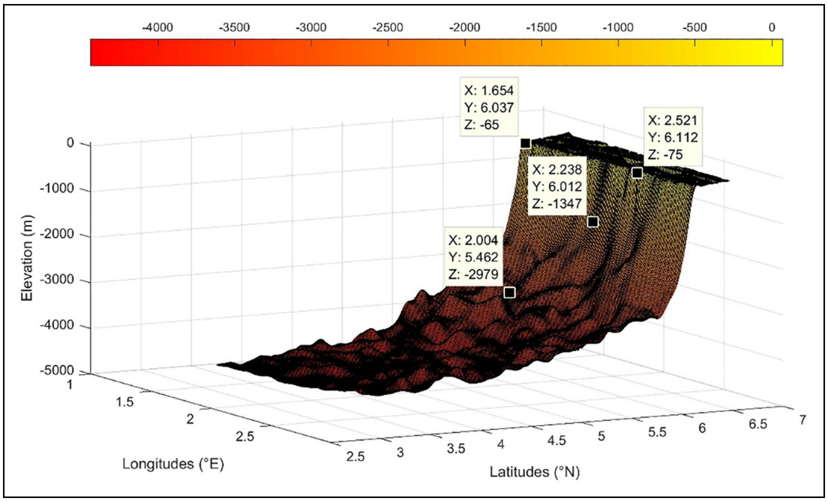

Figure 4. Sea depth in Benin's EEZ.

the annual average of wind speed in Benin Republic's EEZ in 2013 is presented in Figure 3. From this figure, it can be noticed that wind speed at 10 m varies from 5 to 6 m/s.

Bathymetric data. Bathymetry refers to sea depth. The greater the bathymetry is, more complex and expensive will be the foundation of wind turbine to be installed. In order to study technical feasibility of offshore wind energy, it is important to consider bathymetric data. The spatial visualization of bathymetric data in Benin's EEZ is presented at Figure 4. This data are obtained from the General Bathymetric Chart of the Oceans (GEBCO) website (GEBCO, n.d.). In this figure, it can be noticed that the sea depth reaches 4000 m below water level within the EEZ.

The literature reports that wind turbines foundation can be installed into three classes of sea depth: shallow waters (0–30 m), transitional waters (30–50 m), and deep-waters (50–200 m) (Oh et al., 2018). Considering the deep-water limits, bathymetry values between 0 and 250 m are plotted in Figure 5. These values appear between 6.0°N latitude and the coastline latitude.

Spatial variability of wind energy potential at several heights

Wind energy potential in Benin's EEZ at 10 m height is presented at Figure 6 using equation (9). From the analysis of this figure, it can be noticed that wind energy potential in Benin's EEZ at 10 m height varies between 129.1 and

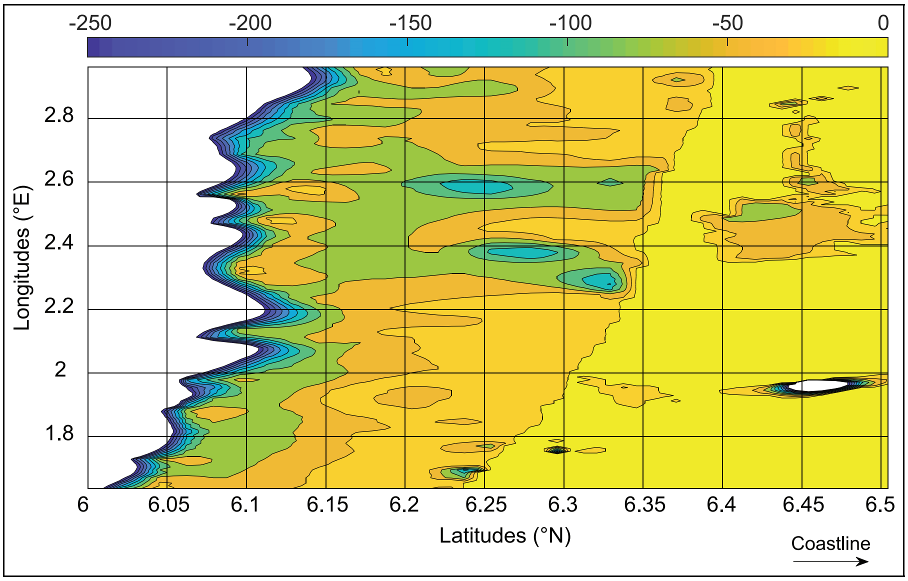

Figure 5. Sea depth between 6°N and coastline latitudes.

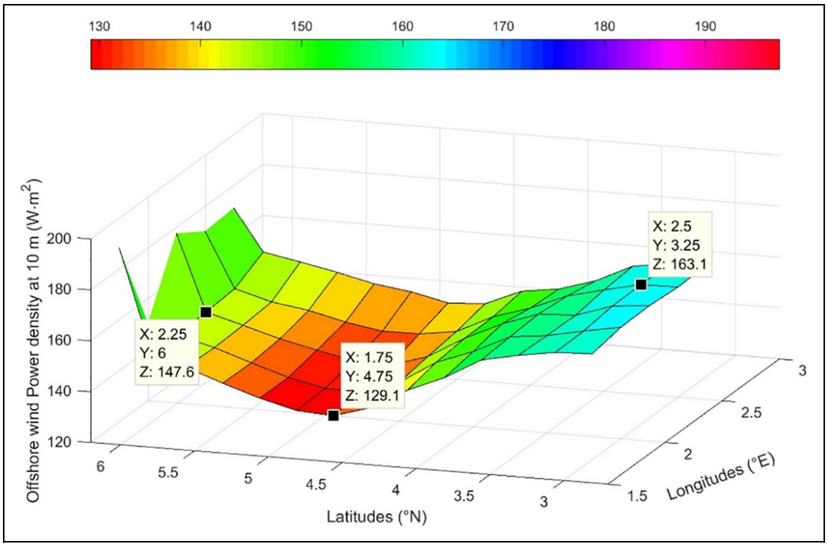

Figure 6. Spatial distribution of wind power density at 10 m height in Benin Republic's EEZ.

197.3 W/m^2. The lowest values of potential appears in between latitude 4°N and 5°N, whereas the highest appears close to the shore at latitude 6°N and the lowest latitudes in the country EEZ near 3.35°N.

Figures 7 to 10, respectively, present the spatial distribution of wind power density at 50, 80, 100, and 120 m. Wind power density distribution is obtained after extrapolating Weibull parameters at these heights.

By analyzing Figure 7, it can be seen that wind energy potential at 50 m varies between 409.5 and 575.9 W/m^2. The lowest values are located in the central part of the EEZ. The highest values are located close to the shore and at the lowest latitudes within the EEZ. In Figure 8, spatial distribution of wind potential at 80 m has similar variation as for 50 m. In this case, the potential varies between 621.4 and 850.4 W/m^2.

Figure 9 shows the spatial distribution of offshore wind power density at 100 m height. It can be seen that wind potential varies between 769.6 and 1039 W/m^2. The maximum value of the power density is located close to the shore in latitude 6°N range.

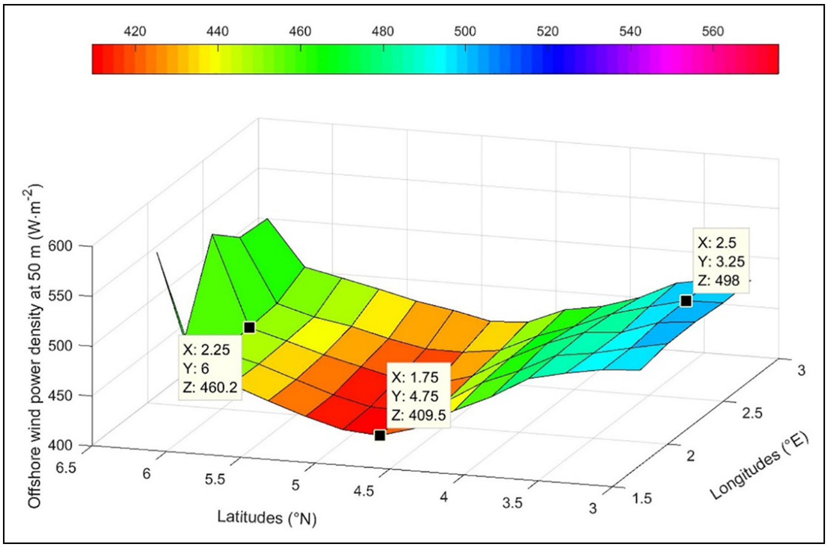

Figure 7. Spatial distribution of wind power density at 50 m height in Benin's EEZ.

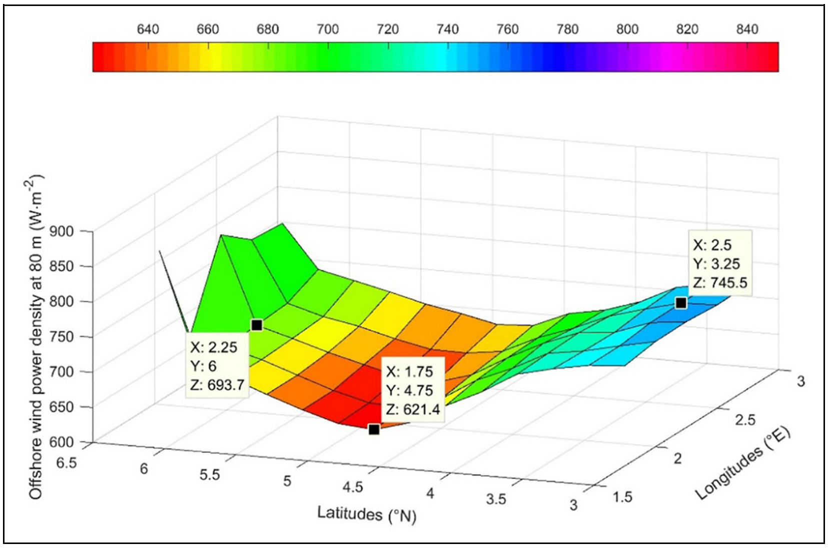

Figure 8. Spatial distribution of wind power density at 80 m height in Benin's EEZ.

In Figure 10, the wind power density at 120 m varies between 924.3 and 1233.5 W/m^2. The maximum value is located close to the shore like in the previous cases.

We labeled on each of these figures wind power density at the same location coordinates, which is summarized in Table 1. The general tendency from the analysis of Table 1 is that wind potential greatly increases with height.

Discussion

Wind energy potential in Benin Republic can be classified using international standards. Such classifications offer the advantage of comparison with other countries wind resources. Referring to National Renewable Energy Laboratory (NREL) classification presented in Allouhi et al. (2017), Benin's offshore wind power density falls into Class 4 ($400\ \mathrm{W/m^2} \leqslant P \leqslant 500\ \mathrm{W/m^2}$) and reaches Class 5 ($500\ \mathrm{W/m^2} \leqslant P \leqslant 600\ \mathrm{W/m^2}$) close to the shore at 50 m. This is interpreted as good for grid-connected wind power generation. This potential is comparable with

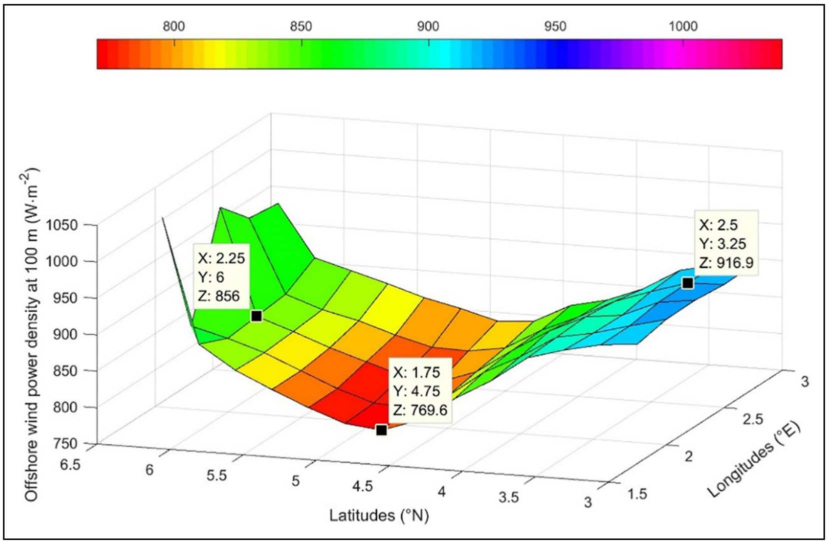

Figure 9. Spatial distribution of wind power density at 100 m height in Benin's EEZ.

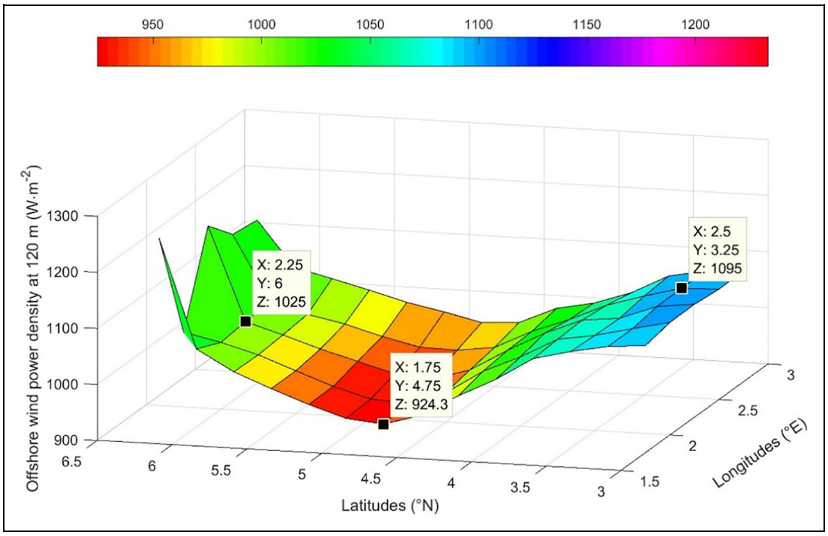

Figure 10. Spatial distribution of wind power density at 120 m height in Benin's EEZ.

Table 1. Wind power density at 50, 80, 100, and 120 m for specific locations.

Coordinates	50 m	80 m	100 m	120 m
Longitude 2.25°E, Latitude 6°N	460.2	693.7	856	1025
Longitude 1.75°E, Latitude 4.75°N	409.5	621.4	769.6	924.3
Longitude 2.5°E, Latitude 3.25°N	498	745.5	916.9	1095

similar studies conducted in Morocco's coastal regions where wind power was also interpreted as good for grid-connected wind power generation (Allouhi et al., 2017).

A more general classification table is presented in Oh et al. (2012) which includes wind classification at 50, 80, 100, and 120 m. The wind potential classification at 50 m is concordant with the table presented in Allouhi et al.

(2017). From Figure 8, it can be noticed that wind potential at 80 m falls into Class 5 ($620\ \mathrm{W/m^2} \leqslant P \leqslant 740\ \mathrm{W/m^2}$) at some locations and reach Class 6 ($740\ \mathrm{W/m^2} \leqslant P \leqslant 970\ \mathrm{W/m^2}$) close to the shore. Wind resource at 100 and 120 m heights falls into Class 6 ($820\ \mathrm{W/m^2} \leqslant P \leqslant 1060\ \mathrm{W/m^2}$at 100 m and $880\ \mathrm{W/m^2} \leqslant P \leqslant 1160\ \mathrm{W/m^2}$). Therefore, wind resource at 100 m reaches the Class 7 ($P > 1060\ \mathrm{W/m^2}$) close to the shore. Thus, offshore wind energy potential in Benin Republic is viable for grid-connected generation starting from 50 m height.

The potential is significant near to the shore and at the lowest latitudes in the EEZ map. One should prefer installing wind farms at latitudes closer to the shore to reduce grid connection costs. It is also important to point out that offshore wind turbine cost strongly depends on the foundation cost. The deeper the sea, the more complex the foundation technology and therefore the cost. According to the information reported in Wind Europe (2013), current commercial foundation substructures are economically limited to maximum water depths of 40–50 m for fixed foundations. Some other articles report foundations up to 60 m for fixed foundations types and greater than 100 m for floating types (WindPower Offshore, 2013). Considering bathymetric data (Figure 4), the sea depth can reach 4000 m. But the potential is economically exploitable for sea depths up to 60 m (fixed foundations type). Thus, the region close to the shore in Benin's EEZ represents the best compromise between wind potential viability and foundation complexity.

It is also worth pointing out that this study did not cover economic feasibility of offshore wind energy in Benin's EEZ. Thus, more detailed studies should be conducted in order to assess the techno-economic viability of offshore wind energy projects in Benin's EEZ.

Conclusion

This article has analyzed the viability of offshore wind energy in Benin Republic's EEZ. The spatial distribution of wind power density has also been analyzed at several heights. It was found that Benin's wind resources are viable starting from 50 m and favorable for offshore wind power generation. This study contributes to identify a new potential energy resource for Benin Republic. It can constitute a strong tool motivating politics to consider wind power generation as an alternative to reduce the country's energetic dependency on nearby countries. It is also important to point out that further studies must be conducted in order to assess the techno-economic feasibility of an offshore wind farm in the country.

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