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Wave Energy Resources Assessment Offshore Benin from ERA Re-Analysis: Gulf of Guinea

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Authors' contributions

This work was carried out in collaboration between all authors. Author GHH designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors BBK and MAH managed the analyses of the study. Authors BNT and VIM managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Wave energy recovery in coastal zones can provide mitigation of flooding and play a very important role in the protection of the coastline.

Wave energy potential off the coast of Benin has been investigated from ECMWF ERA reanalysis (ERA40 + ERA-Interim). ERA data have been adjusted with in situ data coming from the buoy installed off Autonomous Port of Cotonou (Benin) over a period of 60 years. Next, wave energy resources have been evaluated using the Wang and Lu [1] model for medium water depths.

The simulated results showed that in Benin's coastal area, wave energy is moderate and available. At a seasonal scale, wave energy increases from January to August, decreases until December with values ranging from 9.84 to 22.35 kW/m and an average of 15.64 kW/m. The maximum value has been observed in summer and autumn. At the inter-annual scale, an increasing trend of wave

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energy has been observed with a fluctuation of about of 2.47 kW/m. Wave energy resource available in Benin's coastal area has been evaluated to 144.99 kWh/m per wavefront.

Wave energy resources would be an efficient supplemental source, and its exploitation would contribute to energy self-sufficiency and play an important role in the coastal protection of the country.

Keywords: Coastal zone; coastline protection; wave energy increase; Benin; energy self-sufficiency.

1. INTRODUCTION

There are currently, several wave energy recovery devices that can play an active role in coastal protection [2,3]. These recovery devices are particularly interesting since they partially absorb waves in producing electricity, and may thus reduce the wave energy incident on the littoral [4]. Recent studies [2-5] showed that nearshore currents, which are the main factor in driving the coastline dynamics are sometimes even more sensitive than the waves to the nearshore energy extraction. This is explained by the fact that the wave farms induce relevant changes; not only to the wave heights but also to the wave directions [6]. Benin is a coastal country in the Gulf of Guinea (West Africa) with 125 km [7] of coastline. Its coastline is experiencing a serious problem of coastal erosion, consequence of the impact of swells from the South Atlantic on this coast and is accentuated by the human installations: port with dykes blocking the coastal drift, urbanisation with fixing of the dune cord, construction of dams upstream of the rivers, thus reducing sediment inputs [7,8]. It is a country with very low access to energy, less than 27% [9] and almost total dependence from outside [10]. Thus, exploiting wave energy from energy recovery system deployed at sea could not only help increase access to energy but also help mitigate the erosion effects on this coast. Recently, the energy sector is obliged to use alternative sources directed towards environment-friendly renewable energy, ocean waves constitute a potential source of this kind of energy [11]. Ocean energy has a number of significant advantages includes source-predictability, abundance, high load factor and low environmental impact and availability compared to other renewable energy sources and is rightly regarded as one of the renewable energy sources with the greatest potential to replace conventional energy source, because of these advantages [12]. The installation of an energy recovery system in an area is possible only when we have a detailed knowledge of the site wave climates and consequently the energy potential available. The country does not dispose at present wave energy recovery device in its coastal zone while it owns an average exclusive economic zone is about 27,750 km^2. It is then necessary to assess wave energy in the coastal area of the country in order to set up innovative projects of a system for recovery of this energy. Around the world, many countries have assessed the wave energy resource in their coastlines including China [13-15], Korea [16], French [17], Australia [18], England [19], United States [20], South Africa [21] and Morocco [22]. But in Benin's coastal area, no specific study for wave energy potential assessment has been carried until this day.

In this paper, wave energy potential off the coast of Benin has been evaluated and analysed, using the European Center for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA40 + ERA-Interim). ERA data have been fitted with in situ data coming from the buoy installed off Autonomous Port of Cotonou (Benin) over a period of 60 years. Wave energy has been estimated using the Wang and Lu [1] model for medium water depths.

2. MATERIALS AND METHODS

2.1 Study Area

Benin’s coastline, 125 km long, is located between the longitudes E1°5 and 2°5E and the latitudes 5°N and 6°N and facing South Atlantic Ocean (Fig. 1). It is an open environment exposed to long swell waves. It is an environment dominated by the influence of waves of moderate energy (mean significant wave height Hs = 1.36 m, mean peak period Tp = 9.4 s) coming from mid-to high latitudes (45–60°) in the South Atlantic as well as to locally generated short-waves in the tropical band (latitudes 6°N-15°S) [23,24] with an S-SW incidence (incidence on the coast between 4 and 9°) [8,23,25].

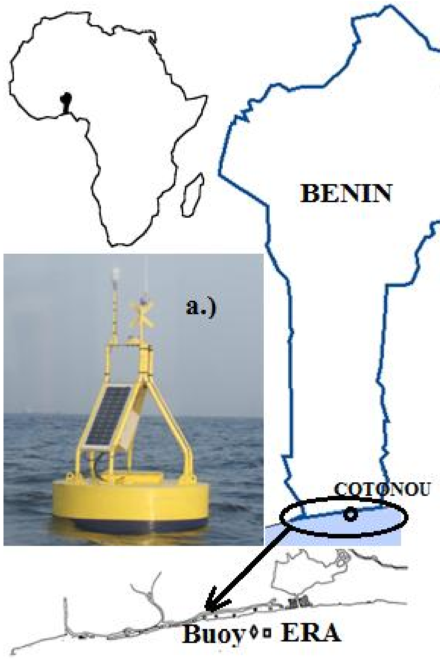

Fig. 1. Sketch of study area (Benin, Gulf of Guinea). Location of ERA and (a) oceanographic buoy

2.2 Data Sets

2.2.1 Buoy data

Wave parameter data from the buoy deployed offshore about 6 Km from the Autonomous Port of Cotonou and more than 15m deep at the coordinates (latitude 6°18'49 N, longitude 2°28'46E) are used (Fig. 1). Waves parameters (Hs, Tp and wave peak direction (Dp)) are recorded every 30 min (24 daily data). Buoy data used here cover the period from December 2015 to October 2016.

2.2.2 ERA reanalysis

The simulations used were provided by ERA40/ERA-Interim of the European Center for Medium-Range Weather Forecasting (ECMWF). It has been reported that the ERA dataset contains some inhomogeneities in time and that it underestimates high wave heights [26] but corrected datasets for the significant wave height have been produced [27]. It uses all available observations to constrain the analysis [28]. The wave parameters (H**s**, T**p** and D**p**) are stored four times a day, and then have a temporal resolution of 6 h. The outputs used are calculated at the point (latitude 5°N; longitude 2°5E) for ERA40 (2.5x2.5°) and (latitude 6°N; longitude 3°E) for ERA-Interim (1.5x1.5°). ERA40 datasets cover the period 1957 to 2002 and ERA-Interim 2002 to 2016. Benin's country is still in its early days in the field of marine renewable energies. No wave energy recovery device is yet installed in the maritime area of the country. The first research began in 2015. But, the potential has not been evaluated from a long series of data. It is therefore appropriate in the context of the promotion of renewable energies in Benin's country to explore this energy source by studying the potential available in this area.

2.3 Data Validation

A comparison between the ERA model outputs and the buoy data indicated an over-estimation of the extremes at the reanalysis with respect to the buoy data. Although the mean values are well described, it thus appears that the model reproduced the large swells (H**s** > 1m) but missed the small ones (H**s** < 1m). The correlation between the buoy data and the model outputs ($R^2 = 0.80$ for H**s**, $R^2 = 0.49$ for T**p**) made it possible to consider an adjustment between the significant heights **Hs**, peak period T**p** observed (buoy) and estimated (ERA). The one realised here is linear and is presented in Fig. 2 (for H**s** and T**p**) and is written by equation (1):

$$\begin{cases} H_{sb} = 1.032 * H_{sm} - 0.104 \\ T_{pb} = 0.545 * T_{pm} + 0.464 \end{cases} \tag{1}$$

where H_{sb} , T_{pb} : represents respectively the significant height and the peak period of the waves measured by the buoy and H_{sm}, T_{pm} derived from ERA. This adjustment is used to characterise wave average energy in Benin coastline area.

2.4 Theory

2.4.1 Wave power estimation

For wave energy resources assessment, wave power density is the most important characteristic, which has been typically calculated in recent studies by integrating model spectra based on numerical wave models [14]. In shallow or medium water depths, the nearshore effects have been considered, when calculating the waves power density including (refraction, shoaling, and bottom dissipation), and sheltering by the coastline or adjacent islands [29]. Hence, in shallow water, the wave power can be obtained using the following expression (equation (2)) [1]:

$$P = \frac{1}{T}\int_0^T \int_{-h}^0 (p + \rho g z) u dt dz \quad (2)$$

where t: Time (s); T: Wave period (s) and z: Water depth (m), u: wave velocity (m/s); h : water depth, ρ : seawater density, and p: pressure (Pa).

The integral of equation (2) over the wave period and the water depth conduced to P. Thus, P can be calculated using [30] by equation (3):

$$P = \bar{E} C_g \quad (3)$$

Where $C_g$denotes wave group velocity and $\bar{E}$ the wave energy density. $\bar{E}$(J/m^2) can be expressed by equation (4):

$$\bar{E} = \frac{1}{16}\rho g H_s^2 \quad (4)$$

The power can be rewritten by equation (5) [14]:

$$P = \bar{E}\left[\frac{gT_e}{2\pi}\tanh(kh)\right] P_1 \quad (5)$$

The wave number k (m^{-1}) as a function of λ (wavelength) (m) is giving by equation (6):

$$k = \frac{2\pi}{\lambda} \quad (6)$$

and

$$P_1 = \frac{1}{2}\left[1 + \frac{2kh}{\sinh(2kh)}\right] \quad (7)$$

In deep water, ($\frac{h}{\lambda} \geq \frac{1}{2}\,; P_1 = \frac{1}{2}\ and\ \tanh kh \simeq 1$) were included in Equation (3) and rearranged conduced to the equation (8):

$$P = \frac{\rho g^2}{64\pi} H_s^2 T_e \quad (8)$$

In the shallow water,($h/\lambda < 1/20$, $P_1 = 1$ and $\tanh(kh) = \frac{2\pi h}{\lambda}$). Equation (3) can then be rewritten by equation (9):

$$P = \frac{1}{16}\rho g H_s^2 \sqrt{gh} \quad (9)$$

For medium water depths, ($1/20 < h/\lambda < 1/2$), we must consider the shallow water correction and P can be calculated using equation (10) [14]:

$$P = \bar{E}\left(\frac{gT_e}{2\pi}\tanh(kh)\right) * \left[\frac{1}{2} * \left(1 + \frac{2kh}{\sinh(2kh)}\right)\right] \quad (10)$$

with

$$\lambda = \frac{g}{2\pi} T_e^2 \quad (11)$$

In which, P: wave power per unit of crest length (kW/m), H_s: the significant wave height, T_e: the energy period, ρ: seawater density (assumed to be 1025 kg/m) and g is the gravitational acceleration (assumed to be 9.81 N/kg). T_e is computed as a function of spectral moments by equation (12) [12,31]:

$$T_e = \frac{m_{-1}}{m_0} \quad (12)$$

T_e can be approximated by equation (12) when the value of T_p is known [12, 22, 31], using equation (13):

$$T_e \simeq \alpha T_p \quad (13)$$

where α: is the coefficient that depends on the shape of the wave spectrum (e.g. 0.86 for a Pierson-Moskowitz spectrum) [32].

More conservative assumption ($\alpha = 0.90$ or $T_e \simeq 0.9 T_p$) has been adopted [31].

This assumption introduces uncertainty in the resulting wave power. However, the errors in the period are less significant than errors in wave height since P is proportional to T_e and to the square of the H_s [32]. The buoy ALIZE is deployed offshore off Benin's coastline about 6 Km at 15 m deep corresponding to medium water. In this work, the equation (10) is used for wave power calculation, assuming T_e = T_p.

2.4.2 Wave energy resource

The total wave energy resource at the extraction point is calculated using Equation (13) which uses the probability occurrence of having certain Hs and Tp [12]. Annual wave energy density of the study area can be determined using equation (14) [6, 33-35]. The 60-year average probabilities of occurrence of all wave height-wave period combinations for the extraction point can be deducted from Table 2, and presented in the form of wave scatter table. This table enables the prediction of overall variability of the extraction point.

$$P_{av} = \sum P * Prob \quad (14)$$

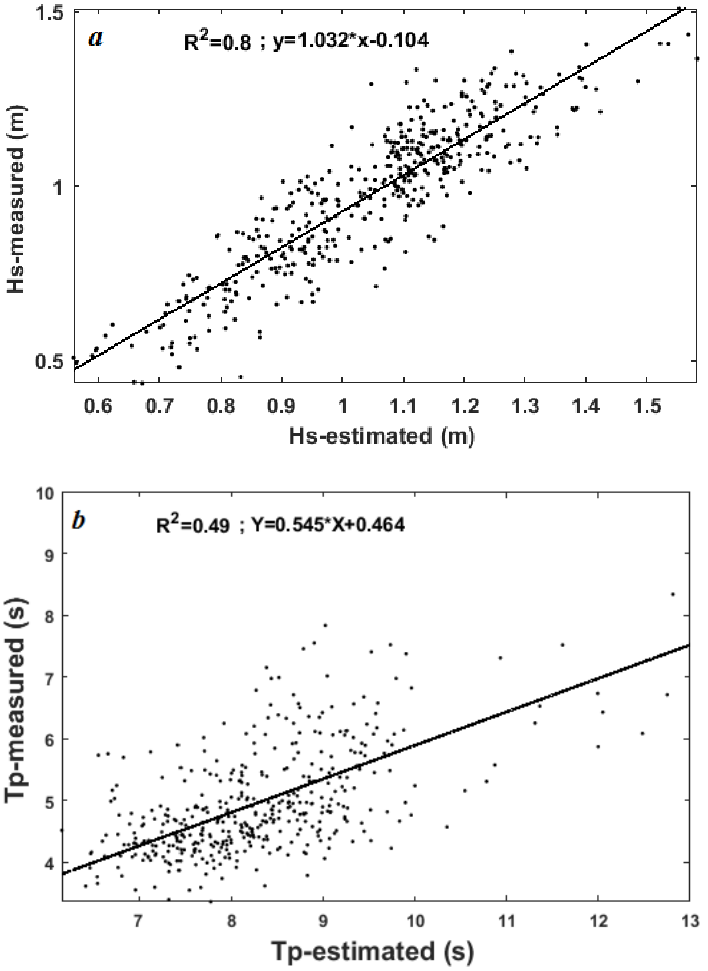

Fig. 2. Data measurements (Buoy) versus ERA reanalysis, (a) Significant wave height Hs and (b) wave peak period Tp

Total wave energy storage E_T per unit zone is calculated to study the available wave energy resources. By multiplying the annual average wave energy P_{av} by the number t_h of hours in a year, approximately $t_h \approx 8766$ hours [36] yield the total wave energy storage, considering equation (15):

$$E_T = P_{av} * t_h \tag{15}$$

3. RESULTS AND DISCUSSION

3.1 Sea-wave Instantaneous Characterisation

On the one hand, wave conditions in the area have been analysed. On the other hand, wave energy resources have been assessed.

Table 1 shows the average sea-wave regime in terms of Hs and Tp and Fig. 3 indicates the compass rose of wave directions D**p**-H**s** for the 10 months and a half period of buoy dataset. They show that in Benin coastal area, the significant wave height can reach more than 2.5 m. The wave periods range from 4 to 14 s and mean wave directions from 180 to 227° and 165 to 180° (S-SW clockwise). This variation is similar to the result obtained by [8,24]. In general, the waves have significant heights between 0.5 and 2.53m from the South-West quadrant, **i.e.**, 190 to 235° (S-SW clockwise). The most frequent wave periods are between 5.2 to 10 s. The interval 6-9 s has the most occurrences. It should be noted that several wave trains are concomitant in the Gulf of Guinea even but the peak energy is dominated by long swells of the south-west. This is due to the fact that the coast is quite far from the swelling generation zone to be affected by local and remote waves, which facilitates the coexistence of multiple wave generation zones [23].

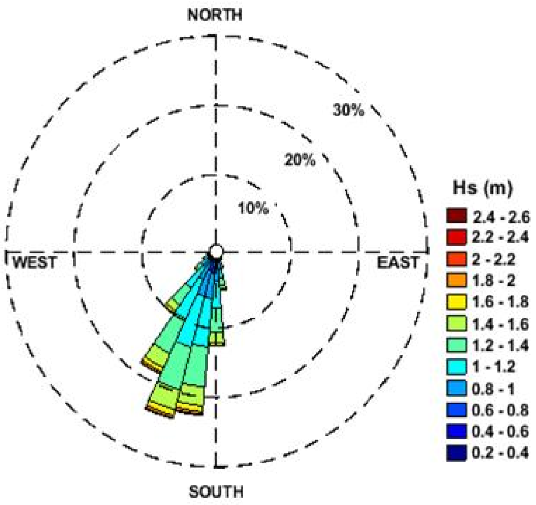

Fig. 3. Compass rose of wave directions for the period 2015-2016 in Benin coastal area from buoy data sets

3.2 Sea-wave Long Term Characterisation

Equation (1) has been used to estimate wave parameters for long-term consideration of wave characterisation and then for wave energy resource. Fig. 4 shows the average the compass rose of wave directions D**p**-H**s** for the 60-year period of ERA reanalysis dataset. The highest values of Hs and Tp occur mainly during summer months (June to August) as expected with a substantial reduction in winter months (September to November). In summer the majority of H**s** averaged occurrences are found in the interval of 0.5 to 2.1m (mean value ≈ 1.42m) (with the most frequent values from 1.5 to 2 m), associated with mean wave directions from the South/South-West (182-210° clockwise). In winter, Hs values mainly range from 0.5 to 1.8 m (mean value ≈ 1.23m) from the South/South-West (195–205° clockwise). This observation is confirmed by wave characteristic at the seasonal scale, Fig. 5.

Table 2 indicates the average of the sea-wave regime in terms of H**s** and T**p** from Equation (1). The most frequent for wave periods (T**p**) is between 6.5 to 12 s and 1 to 2.5m for wave height. The interval 7-12s has the most occurrences for wave period and 1 to 2 m for wave significant height. A statistical study shows that 85.47 percent of Tp was greater than 8s.

Fig. 5 shows the averaged sea-wave (60 years) regime in terms of H**s** and T**p**. At the seasonal scale, the maximum values of Hs are observed from May to September ranging from 1.19 to 1.53 m averaged of 1.43 m with peak values in June, July and August. Fig. 5 indicates an increasing tendency of H**s** from January to July and decreasing tendency until December. The seasonality observed is related to wind variability in the Atlantic Ocean. In fact, the winds generated in the South Atlantic maximum in July, increase from January to July and then decrease until December [24, 25, 37]. The peak of the wave, stayed relativity constant with an averaged value of 9.5 s with the highest values from May to August.

3.3 Wave Energy Potential Analysis in Benin Coastal Area

3.3.1 Annual wave energy variability

Fig. 6 indicates wave annual power variability P, from 2002 to 2016 using equation (9) when all types of waves have been taken into account. The figure shows an increasing tendency of wave power ranging from 13.01 to 21.77 kW/m averaged of (16.90± 2.47) kW/m. The majority of P averaged occurrences are found in the interval of 13 and 20 kW.m-1 (with the most frequent values from 16 to 18.5 kW/m). This trend is related to this observed in wave significant height

Table 1. Wave scatter table from *in situ* buoy data parameters (Dec. 2015- Oct. 2016)

Hs(m)	2	418	6728	4853	2144	621	172	60	12	13	0	15023
2.5-3	0	0	0	0	0	0	0	0	0	0	0	0
2-2.5	2	201	632	502	247	49	7	0	0	0	0	1640
1.5-2	0	215	5166	3009	1113	321	98	33	5	4	0	9964
1-1.5	0	2	904	1298	680	207	49	25	6	9	0	3180
0.5-1	0	0	26	44	104	44	12	1	1	0	0	232
<0.5	0	0	0	0	0	0	6	1	0	0	0	7
Tp(s)	<5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	>14	

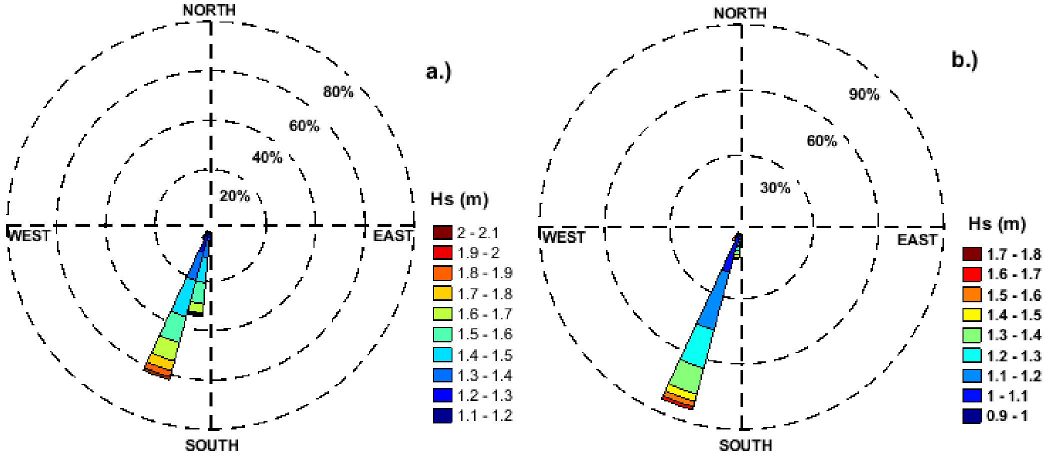

Fig. 4. Averaged Hs-Dp roses of directions in Benin coastal area in: (a) summer and (b) winter

Table 2. Wave scatter table for long-term wave parameters (1957-2016)

Hs(m)	0	88	2304	10081	23053	26366	15580	6116	1752	438	0	85778
2.5-3	0	0	0	0	0	0	1	2	1	0	0	4
2-2.5	0	5	183	1054	1572	164	7	3	2	0	0	2990
1.5-2	0	65	1554	6979	17059	18477	6220	610	22	10	0	50996
1-1.5	0	18	564	2004	4262	7216	8349	4220	772	82	0	27487
0.5-1	0	0	3	44	159	505	974	1198	824	240	0	3947
0-0.5	0	0	0	0	1	4	29	83	131	106	0	354
Tp(s)	< 5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	>14	85778

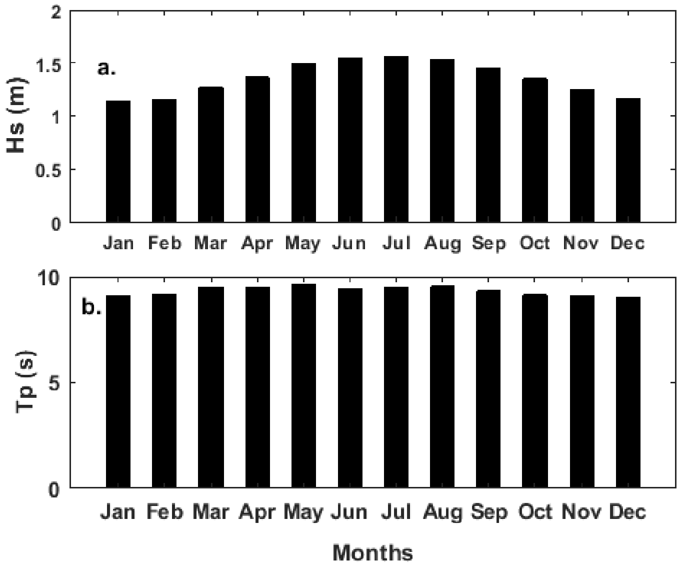

Fig. 5. Averaged of (a) Hs and (b) Tp wave regime in Benin's coastal area

in the Gulf of Guinea [24,37]. In the sub-region, there is no knowledge of work in this area. But further south, along with the South African coast, the average annual wave power available varied from 33 to 41kW.m^{-1} [21], higher (41.21-51.22%) than that found in this work. A further north, on the Moroccan coast, wave energy averaged available (30 kW/m) is also greater (56.33%)

than that observed in our study area [22]. Referring to the global average wave energy map [38], our results seem to overestimate the values contained therein. Indeed, according to this map, wave energy averaged available to Beninese coastal area is between 5 and 12 kw.m^{-1}. It is important to note that this map was carried out with deep water consideration which is not the case of this study where the energy is assessed with medium water consideration.

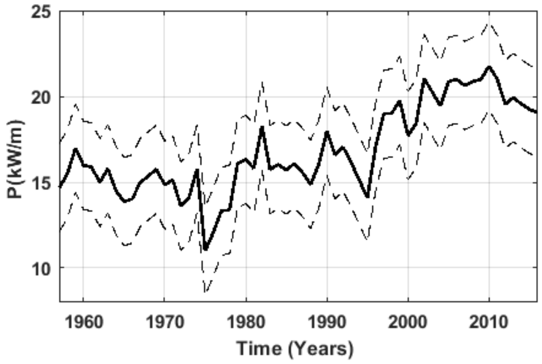

Fig. 6. Annual averaged wave power from 1957 to 2016 (60 years). The dashed lines indicate the standard deviation of annual wave power

3.3.2 Seasonal wave energy variability

Wave energy in Benin's coastal area is strongly influenced by seasonal fluctuations. Fig. 7.a indicates wave power's seasonal variability (P) from 2002 to 2016 using equation (9) when all types of waves have been taken into account. Fig. 7.a shows an increasing tendency of wave power from January to August and decreasing tendency until December with values ranging from 9.84 to 22.35 kW/m averaged of (15.64 ± 2.33) kW/m. The result can be attributed to wave significant height in Gulf of Guinea (Fig. 5.a) [8]. The low values were observed from December to February where the power is less than 15 kW/m and the maximum values from April to November where the power is greater than 15 kW/m, pronounced seasonal variations in the wave energy are present in this area. Fig. 7.b indicates thus, the assessment of wave energy for the different seasons of the year. The wave energy is larger in summer (24.5 kW/m) and autumn (23 kW/m) than at in spring (16 kW/m) and winter (14-16 kW/m). Therefore, wave energy is mainly exploited in autumn and summer. This variability is similar to the global seasonal distribution of average wave power [32]. Indeed, wave energy average estimated by the global distribution is less than 11 kW/m in January and between 11-22 kW/m in August.

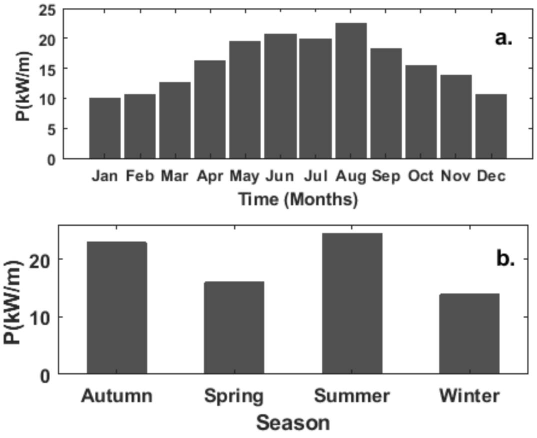

Fig. 7. Average wave energy density: (a) monthly and (b) for each season of the year in Benin marine area

3.3.3 Wave energy resource in Benin coastal area

Total wave energy is defined to denote reserve. The wave energy reserve is one of important factors for wave energy assessment in typical areas [14]. The richness of wave energy resources is also an important factor in identifying ideal locations for wave power plants. It has been indicated that wave energy is available when P ≥ 2 kW/m and rich when P ≥ 20 kW/m [36,39-40]. The total storage per unit zone of wave energy E_T is calculated to study the available wave energy resources. Annual wave energy average Pav has been estimated using equation (15). The results are mentioned in Table 3 and indicate that energy in Benin coastal area is moderate and available.

Table 3. Wave energy resource in Benin coastal area

Average annual wave energy density (kW/m)	Probability of exploitable SWH (%)	Annual wave energy storage (MWh/m)	Status
16.90kW/m	97.87	144.99	Available

where SWH: Sea wave height

4. CONCLUSIONS

Wave energy resources have been assessed for the first time in Benin's coastal area using sixty years ERA reanalysis of European Center for Medium-Range Weather Forecasts (ECMWF) wave data adjusted with buoy data deployed offshore about 6Km from the Autonomous Port of Cotonou (Benin) and more than 15m deep at the coordinates (2°28'46E, 6°18'49N).

The results show that wave energy in this area is moderate and available. Wave energy seasonal variation is highest influenced by S-WS clockwise wave height which reaches its maximum from May to September. A large wave energy P values have been observed from 13.01 to 21.77 kW/m at the inter-annual scale and 9.84 to 22.35 kW/m at a seasonal scale. Wave energy resource available in Benin's coastal area has been estimated to 144.99 MWh/m per wavefront.

Wave energy resource would be an efficient supplemental source, and its exploitation contributes to energy self-sufficiency and would play a key role in the coastal protection of the country. The buoy was the first installed off the coast of Benin, to study and analyse the temporal variability of hydrodynamic parameters, consequently to assess wave energy. The installation of this buoy was a success for the description of wave regime off the coast of Benin and wave energy resources assessment.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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