NIPES
Journal of Energy Technology and Environment
Journal homepage: www.nipesjournals.org.ng

Determination of the Wave Power Potential for Delta State, Nigeria

Muhammed K. Abdulkadir* and Amarachukwu A. Ibe
Physics Unit/School of Basic Sciences, Nigeria Maritime University, Okerenkoko, Nigeria
*Corresponding Author: kabiru@nmu.edu.ng

Article information

Article History
Received 30 October 2024
Revised 10 November 2024
Accepted 16 November 2024
Available online 19 Dec 2024

Keywords:
Significant wave height, mean wave energy, wave power density, Wave energy density.

OpenAIRE
https://doi.org/10.5281/zenodo.14529736

https://nipes.org

Abstract

Wave energy potential for three points located in Delta state of Nigeria along the Gulf of Guinea has been determined. The points were indicated as NDelt1 located 0.63 km distance from the shoreline along Benin river, NDelt2 located 2.89 km from the shoreline along Escravos river and NDel3 located 2.41 km distance from the shoreline along Forcados river bars. Ten years (2014 to 2023) dataset at the horizontal resolution of 0.5^0 X 0.5^0 with hourly temporal resolution were been obtained from ERA5 of the European Council for Medium Range Weather Forecast (ECMWF). The results shows that the average wave power densities of NDelt1, NDelt2 and NDelt3 are 23.96, 25.71 and 23.13 kW/m respectively. The wave power density is maximum during summer season and minimum during winter for both locations. During the summer season, NDelt1 has the average power density of 36.01 kW/m with NDelt2 having 43.38 kW/m and NDelt3 has 35.16 kW/m. while during winter season, NDelt1, NDelt2 and NDelt3 has wave power densities of 12.35 kW/m, 27.1 kW/m and 12.99 kW/m respectively. The total wave power and energy density for the three stations are 72.79 kW/m and 6159.17 MWh/m indicating that the wave resource for electricity generation is available.

1. Introduction

Resources, designs and economic analysis associated with renewable energy remain one of a key figure in the modern research [1,2]. This became necessary as a result of too much concern on the increase in climate change. However, as the water covered two-third of the world surface, abundant resources within ocean could provide adequate energy security globally without contributing a single portion to global warming [3]. Different technologies applied on different resources in the ocean were been utilize to generate electricity[4]. One of such technology is the utilization of the kinetic energy of water in the ocean for electricity production. Even though sea water wave study might have a little bit complex compared to other renewable sources due to the constraints associated with it, but enormous energy resources were eminent as the density of water is much higher to generate reasonable amount of electricity [5].

Spatial and temporal resolution should be considered when dealing with the variation of wave energy distribution. The effect of bathymetry as well as the timescales for specified locations within the ocean coincide with the sea bed characteristics and it associated energy [6,7]. Therefore, appropriate long-term statistical assessment for the distribution of wave energy resources to identify a suitable location should be carried out before setting a wave power plant project. This will also help in selecting the optimization type on the wave energy converter (WEC) and it operational requirement [8].

As the result of non-stop effort in the development of the wave model numerically, these enhanced the transformation model associated with high-spatial resolution designed primarily for coastal finite water depth or shallow) environments [9]. The transformation models played an important role in an understanding the constraints associated in all the four wave processes of the coastline water. These processes involved the generation process due wave growth by wind, propagation process (reflection, refraction, diffraction, blocking and shoaling), the transformation process (quadruplets and triad nonlinear wave-wave interactions), and dissipation process (depth-induced wave breaking, white capping and bed friction) [10].

Several researches have been executed using wave data obtained from difference forms (measured, satellite and simulations) and timescales for various locations across the globe. For example, forecast series data for the period of seventeen years (1996 to 2013) has been used to estimate wave energy resources of the Island of Menorca in space. The data used was from the hindcast wave climate database using WAM model under the wind production constraint of HIRLAM territorial atmospheric model. The data obtained was from the buoy at a depth of 300 m was used to validate the WAM data. The average wave power obtained was 8.9 KW/m with the average annual energy of 78 MWh/m [11]. AnsWAM model for wave direction hindcast (1997 to 2008) was used to estimate the average power of 25 – 35 KW/m with the convey average energy of 800 – 1100 GJ/m of energy in a year within the Tasmania/Victoria, South Western and South region all in Australia [12]. Parameters of the significant peak periods, wave directions and wave height hindcasted for twenty-four years' periods (1979 - 2003) was used to assessed the maximum monthly averaged wave power of around 25 K/m of the Southwestern side of the Korean Peninsula in winter. The parameters used was extracted from wave buoy deployment and compared with the simulated data obtained from SWAN which were validated based on adjustment procedure [13].

Wave energy resources were assessed via numerical simulation of third-generation ocean model for the period of ten years (2001 to 2010) using high-resolution wave assessment in Mediterranean Sea with Western Sardinia coast and Sicilian Channel having profitable territories for wave power projects [14]. A near-shore of 50 m depth parameters of 15-years ocean wind-wave through model simulation data has been used to obtain an average wave energy of nearly approximation of 200 Mwh/m within the part of Peniche of Nazare in Portuguese coast [15]. Assessment of wave Energy Potential along the Erosion Prone Coast AT Ullal, Karnataka in India was carried out using MIKE 21 SW simulated data and the average wave power in the two points were 17Kw/m and 21 kW/m [16]. Another wave energy research was taken place for four points in Northern Zhoushan Archipelogo using SWAN wave model for 10 years period and average wave energy potential of 349MW, 302MW, 318MW, and 387MW were obtained in those islands respectively [17]. Alternatives methods and data sources has been used for similar purpose to harness the wave resources in various coastlines of many countries including China, England [18, 19, 20], Italy [21], United State States [22].

In Africa, wave resources assessment were being carried out in countries like Cape Verde from a period of 1979 to 2009 with an annual average power of 18kW/m [23], Morocco [24] and Benin Republic. A wave resources assessment was conducted in Benin Coastlines in which a wave buoy was deployed at a depth of 15 m and 6 km offshore away from Cotonou port for the period of eleven months (December 2015 to October 2016). The wave parameters (significant wave height, mean wave period and direction) with a temporal resolution of 6 h obtained from the wave buoy was used to validate ERA40/ERA-Interim provided by the European Centre for Medium-Range Weather Forecasting (ECMWF). The wave energy resource available in the Benin's Coastline has been estimated to be 144.99 MWh/m per waveform [25].

In Nigeria, research was carried out on the statistical wave description of Forcados Offshore for shallow water using two years (1980 to 1982) in-situ measurement dataset obtained from Shell Nigeria to predict extreme short- and long-term significant wave heights in that location. The result shows that the description of the wave is not dominated by the swell and further research was encourage using adequate data [26].

Niger-delta of Nigeria is located in the Gulf of Guinea which falls within the latitude (4.15^{0}N–7.17^{0}N) and longitude of (5.050E – 7.17^{0}E) is a wetland of about 70,000 km^2 covers by rivers, streams and creeks with low lying swamp terrain. This makes it the largest in Africa and largest in the world when it comes to wetland [27, 28]. This shows that wave resource potential is likely available.

However, despite the fact that the communities situated around the study areas has enormous marine resource potential, they relied heavily on diesel generators for electricity generation which is associated with pollution that affect the communities' farming and fishing activities. Hence, there is need in assessing those marine resource potentials. Wave power potential of the site for electricity generation will be considered in this work.

This research will focus on the assessment of wave power potential for three points located at along Benin river, Escravos river and Forcados river. Hence, Benin river will be considered as NDelt1 in this work, while Escravos and Forcados river as NDelt2 and NDelt3 respectively.
Marine renewable energy research is at its early stage of development globally; Hence, Nigeria should not be excluded considering the amount of megawatt of electricity the country is currently generating.

2. Materials and Methods

2.1.Study Area

The total area of study are three points (NDelt1, NDelt2 and NDelt3) covered 4.14 km^2 area marine sites in Delta state, Nigeria. The specified points are 0.63 km from the shorelines (latitude 5.758926°N, longitude 5.065616°E) along the Benin River, 2.89 km from the shorelines (latitude 5.585180°N, longitude 5.170548°E) along the Escravos River, and 2.41 km from the shorelines (latitude 5.377823°N, longitude 5.325080°E) along Forcados River with a depth of 51, 53, and 56 m respectively all situated around the South Atlantic Ocean in the Nigeria Gulf of Guinea.

Figure 1. Satellite image showing area of interest for Wave Data extraction

2.2 Data

The data used in this work are significant wave height, zero wave period and mean wave direction at the horizontal resolution of for the period of ten years (2014 to 2023) obtained from ERA5 of the European Council for Medium Range Weather Forecast (ECMWF). at the horizontal resolution of 0.5^0 X 0.5^0 with hourly temporal resolution. ERA5 data is the fifth generation ECMWF reanalysis for the global climate and weather for the part 8 decades, this data is available from 1940 onwards and updated daily with a latency of about 5 days to replaces the ERA-Interim reanalysis. Reanalysis combines model data with observations from across the world into a globally compete and consistent dataset using the laws of physics called data assimilation based on the method used by numerical weather prediction centres, where a previous forecast is combined with newly available observations in an optimal way to produce a new best estimate of the state of the atmosphere analysis from which an updated and improved forecast is issued.

2.3 Mathematical Equations

The state of the sea or ocean are more understandable based on a factor that represents how the elevations of the surface of sea were been distributed over various frequency bands (f) as well as their directions of propagation (θ). This factor is known as the directional variance wave density spectrum which can be written in terms of the combination of two functions given by [29] as:

$$S(f,\theta) = s(f)D(\theta;f) \tag{1}$$

Where f is the wave frequency and $D(\theta;f)$ been the direction of the spreading function. However, each band of the frequency contained spectral energy within. The quantity of such spectral energy is shown by the spectrum of the wave frequency (f) . Both the two forms of spectra (directional spectrum $S(f,\theta)$ and frequency spectrum $s(f)$ are related by the expression given by [30] as:

$$s(f) = \int_0^{2\pi} (Sf,\theta)d\theta \tag{2}$$

The moment's order of nth of the spectral used to obtained a number of parameters of the sea wave nature characterizing the directional wave spectrum $S(f,\theta)$ expressed by [31] as:

$$m_n = \int_0^{2\pi} \int_0^{\infty} S(f,\theta)\, df d\theta \tag{3}$$

Where $n = -1, 0, 1, 2, \dots \dots$

2.3.1 Wave Climate Parameters

The wave climate of a specified location describing a state of a sea include five non-directional wave parameters known as significant wave height H_e (the mean wave height of the top 1/3 highest of the waves), mean wave period T_m, energy wave period T_e, peak wave period T_p, and zero-crossing wave period T_z are expresses respectively by [32] as follow:

$$H_s = 4\sqrt{m_0} \tag{4}$$

$$T_m = \frac{m_0}{m_1} \tag{5}$$

$$T_e = \alpha T_z \tag{6}$$

$$T_P = f_p^{-1} \tag{7}$$

$$T_z = \sqrt{\frac{m_0}{m_2}} \tag{8}$$

Where m_0, m_2 and m_2 are is the zeroth, first and second order moments of the variance density spectrum defined by [28] as:

$$m_0 = \int_0^\infty s(f)df \tag{9}$$

$$m_2 = \int_0^\infty f^2\, s(f)df \tag{10}$$

$T_P = f_p^{-1}$ been peak wave frequency.

2.3.2 Wave Period Parameter

The parameter α is the coefficient depend on the shape of the wave spectrum. The value of α has been estimated by the Atlantic Marine Test Site in Ireland for the Exploitation of observation to be 0.8 [33]. Another approximation was given by Pierson-Moskowitz spectrum to be 0.89 [34]. Also, analytical derivation of a JONSWAP spectrum with peak enhancement ($\gamma = 3.3$) proposed value given as 0.9 [35]. Exploitation made by NOAA observations within the North-West Atlantic referred the value to be $\epsilon[0.29; 1.5]$ [36]. Other approximations for α include 1.09 [37] and 0.90 taken recently [38]. However, 1.3 will be considered in this study as recommended for Nigeria [39]. Thus equation (7) becomes:

$$T_e = 1.3T_z \tag{11}$$

The state of the sea wave is also described by the directional wave parameter called the mean wave direction, which is the most widely used given by [40] as:

$$\theta_m = m_0^{-1} \int_0^{2\pi} \int_0^\infty \theta s(f,\theta) df d\theta \tag{12}$$

With $S(f,\theta)$ defined by equation (1)

2.3.3. Wave Energy and Power Density

The primary aims in assessing the wave energy potential for electricity generation include the wave power density which could be obtained by expressing the available data from either In-situ measurement, satellite measurement or numerical modelling [41]. Power is the rate at which work is done by pressure forces or the rate at which energy is transported. The wave power density can be calculated from equation (13) given by [42] as:

$$P = \frac{1}{T}\int_0^T \int_{-1}^0 (p + \rho g h) v dt dh \tag{13}$$

Where T is the wave period (s), t is the time (s), v is the velocity of the wave (m/s), h is the depth of the water (m), ρ is the sea water density (kg/m^3), P is the pressure (pa).

The power P and wave energy transport per unit crest length $\bar{E}$ (KW/m) are related by the expression given by [40] as:

$$P = \bar{E}_f = \bar{E}C_g \tag{14}$$

Where $C_g$the rate at which energy is transmitted called group velocity and can be expressed by the equation given by [41] as:

$$C_g = \left(\frac{1}{2}C(1+G)\right) \tag{15}$$

The factor G which can be expressed as:

$$G = \frac{2kh}{\sinh(kh)} \tag{16}$$

G Depends on the water depth, h (m) and wave number, $\left(k = \frac{2\pi}{\lambda}\ (m^{-1})\right)$. C is the phase velocity (m/s).

Where $\bar{E_f}$ is the mean energy flux which is equal to the product of the mean energy density and group velocity. Also, the wave energy transport per unit crest length $\bar{E}$ (KW/m) can be expressed using equation given by [43] as:

$$\bar{E} = \frac{1}{8}\rho g H_s^2 \tag{17}$$

Equation (14) can now be expressed as:

$$P = \left(\frac{1}{8}\rho g H_s^2\right)\left(\frac{1}{2}C\left(1 + \frac{2kh}{\sinh(2kh)}\right)\right) \tag{18}$$

For deep water wave, the rate at which energy is transmitted, is half of the wave speed ($\left(\frac{h}{\lambda} > 0.05\right)$. this shows that $h \longrightarrow \infty$ and $kh \gg 1$. Thus, the wavelength,λ and celerity, c, can be written by the expressions respectively given by [44] as:

$$\lambda = \frac{gT_e^2}{2\pi} \tag{19}$$

$$C = C_d = \frac{gT_e^2}{2\pi} \tag{20}$$

Where T is the period and C_d is the celerity for deep water.

The factor G becomes zero ($G = 0$) and the group velocity,C_g simplifies to

$$C_g = \frac{C_d}{2} = \frac{gT_e^2}{4\pi} \tag{21}$$

Therefore, the expression for wave power transmitted per unit surface area for crest or deep water in equation (14) can be express as:

$$P = \bar{E}C_g = \frac{\rho g^2 H_s^2 T_e^2}{64\pi} \tag{22}$$

Equation (22) depends on H_s^2 and T_e^2

Despite the fact that equation (22) is been derived for deep water purpose, traditionally, previous researches has shown that the equation has been applied from transitional to shallow water depth which could lead to a systematic error of up to 20% [45].

Since the sea water density is assumed to be 1025 kg/m^3, the acceleration due to gravity is assumed to be 9.81 N/kg, and is also known. Then, the approximate expressions for wave power and energy densities are written as the state parameter functions in a more explicit way given by [46] as:

$$P = 0.55H_s^2T_e \tag{23}$$

$$\bar{E} = 628.45H_s^2 \tag{24}$$

Equation (23) and (24) has been used to calculate the wave power and energy densities for the three locations with 0.55 and 628.45 as an approximate constant values depth water calculated from (25) and (20).

3. Results and Discussion

3.1 Data Analysis

3.1.1 Significant wave height, mean wave period and mean wave direction

Table 1 summarized the total amount of significant wave heights data and that of the zero wave period data as well as their percentages obtained from ERA 5 for the three specified locations (NDelt1, NDelt2 and NDelt3). The data ranges covered the period of 10 years (from January 2014 to December 2023). The scattered tables showing the joint relative frequency of occurrences and distributions directional unresolved sea water states between the significant wave heights and mean wave periods for NDelt1, NDelt2 and NDelt3 stations were also been displaced

Table 1. The amount of data (significant wave height and zero wave period) used in the study from 2013 to 2023 along with their range and average values.

Stations	Significant Wave Height (m)				Peak Wave Period (s)			
	Range	Average	Amount of data	% of data	Range	Average	Amount of data	% of data
NDelt1	0.64 - 2.79	1.71	87071	99.4	3.94 – 14.23	10.78	87071	99.4
NDelt2	0.89 – 3.01	1.83	87006	99.3	4.23 – 11.76	10.33	87006	99.3
NDelt3	0.69 – 2.81	1.75	86073	98.3	7.33 – 12.80	10.18	86073	98.3

Table 2: Wave scatter plot showing the wave occurrence of significant wave height and mean wave energy for NDelt1

Hp	0	7	207	1810	9064	3513	10313	38844	18832	4347	133	0	**87071**
3-3.5	0	0	0	0	0	0	0	0	0	0	0	0	0
2.5-3	0	0	8	42	643	71	3	0	0	0	0	0	767
2-2.5	0	5	32	265	1059	233	104	119	41	7	0	0	1865
1.5-2	0	2	118	887	3127	287	1030	9862	5765	611	86	0	21776
1-1.5	0	0	46	595	4053	2386	8112	20431	10272	3651	42	0	49588
0.5-1	0	0	3	21	182	536	1064	8432	2754	78	5	0	13075
> 0.5	0	0	0	0	0	0	1	0	0	0	0	0	1
Tp(s)	> 3	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	

Table 3: Wave scatter plot showing the wave occurrence of significant wave height and mean wave energy for NDelt2

Hp	0	40	101	313	1863	6270	30276	42676	3556	1643	220	48	0	**87006**
3.5-4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3-3.5	0	0	0	0	0	3	21	8	1	0	0	0	0	33
2.5-3	0	0	0	8	42	643	1876	864	121	78	7	0	0	3639
2-2.5	0	1	5	32	265	1650	10159	9032	289	141	21	0	0	21595
1.5-2	0	39	94	218	887	2007	10941	28112	1143	464	87	6	0	43998
1-1.5	0	0	2	55	665	1321	5425	1171	1030	862	105	42	0	10678
0.5-1	0	0	0	0	4	646	1854	3489	972	98	0	0	0	7063
> 0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0

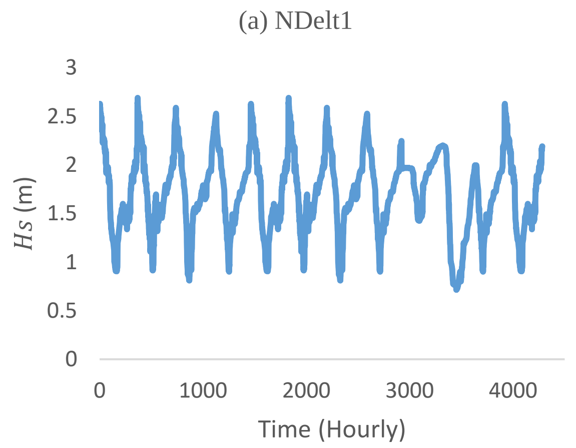
Tp(s)	>3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15

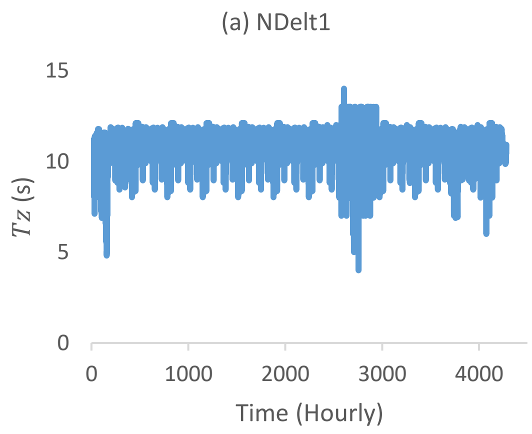
Table 4: Wave scatter plot showing the wave occurrence of significant wave height and mean wave energy for NDelt3

Hp	0	0	0	142	3330	29487	37887	11793	3430	4	0	**86073**
3.5-4	0	0	0	0	0	0	0	0	0	0	0	0
3-3.5	0	0	0	0	0	0	0	0	0	0	0	0
2.5-3	0	0	0	0	643	1876	864	121	78	0	0	3582
2-2.5	0	0	0	45	902	3578	9876	2056	523	0	0	16980
1.5-2	0	0	0	97	1318	20754	17987	5614	1909	3	0	47682
1-1.5	0	0	0	0	321	1425	5671	3030	862	1	0	11310
0.5-1	0	0	0	0	146	1854	3489	972	58	0	0	6519
> 0.5	0	0	0	0	0	0	0	0	0	0	0	0
Tp(s)	>4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	

Table2 shows that out of the total data for both significant wave height and zero mean period, the sea water state with the greatest correlation occurred at 20431 between the significant wave heights of 1 to 1.5 m from the direction of south southwest (193^0 to 222^0) and the mean wave period of 10 to 11 s with the mean direction of wave falls between 190^0 to 219^0 and 171^0 to 196^0 in south southwest clockwise for NDelt1 station.

Table 3 and Table 4, the greatest occurrences happened to be 28112 between the significant wave heights of 1.5 to 2 m with the direction of the wave ranging from 196^0 to 230^0 (S-SW) and mean wave period of 9 to 10 s with mean wave direction 174^0 to 196^0 (S-SW) for NDelt2 station and 20754 correlation at the significant wave height of between 1.5 to 2 m when the mean wave period are within 8 to 9 s at NDelt3 station with the wave direction from 201^0 to 233^0 south southwest clockwise. The mean wave period were obtained using fixed parameter ($\alpha = 1.3$) shown in Table 5, Table 6 and Table 7 for both stations using equation 7 above. However, in Figure 1(a), analyzed the significant wave height data, for NDelt1 which was 2.64 m in the month of June which is highest to 0.71 m in the month of January which is lowest with an average data of 1.71 m.





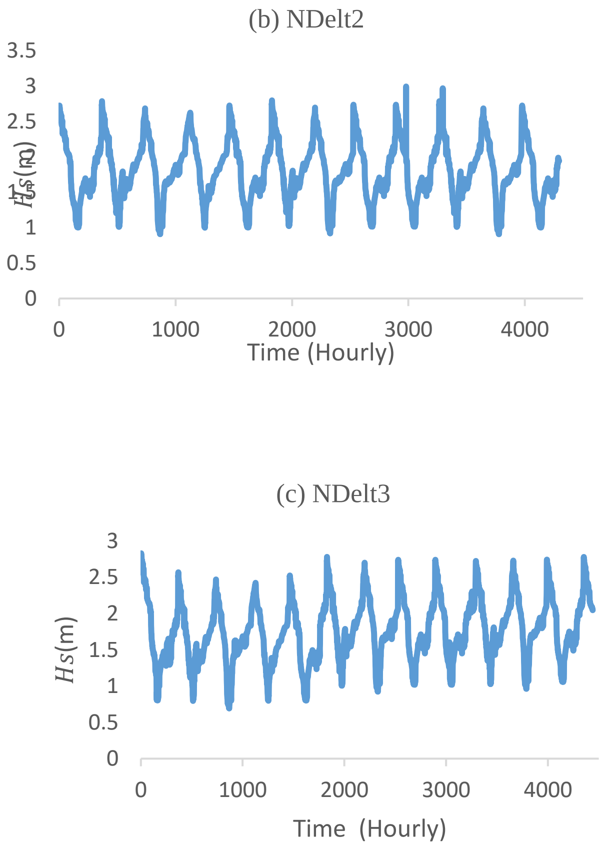


Fig 1: Original time-series of significant wave Height between 2014 and 2023 for (a) NDelt1, (b) NDelt2 and (c) NDelt3

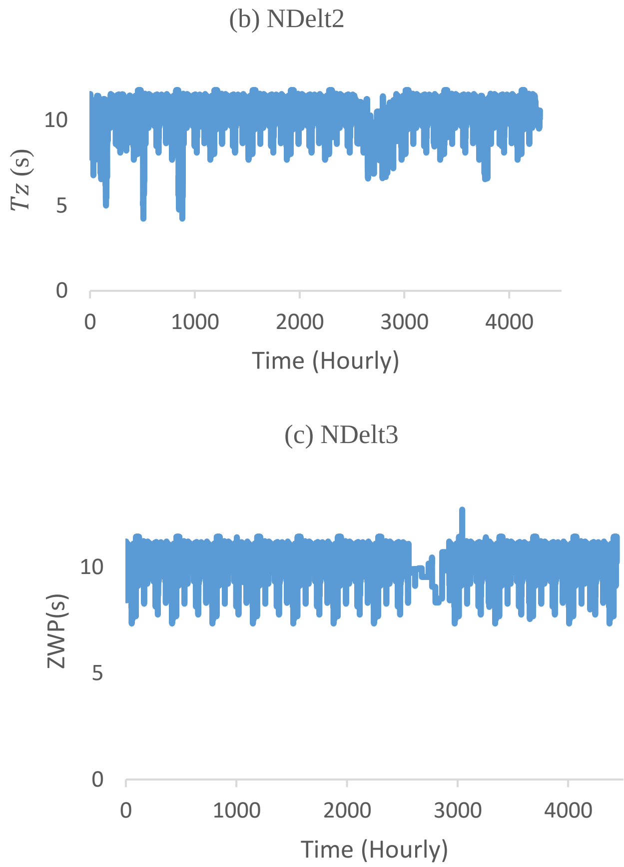


Fig 2: Original time-series of zero wave period between 2013 to 2023 for (a) NDelt1, (b) NDelt2 and (c) NDelt3

Table 5. Average Monthly significant wave height (m), significant wave height square (m²), zero mean period (s), mean wave energy (s) for NDelt1

	Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
H_s	1.16	1.44	1.60	1.71	2.07	2.37	2.19	1.95	1.90	1.63	1.53	1.18	1.71
H_s^2	1.35	2.07	2.56	2.93	4.28	5.60	4.79	3.80	3.59	2.67	2.35	1.39	3.11
α	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
T_z	10.90	10.43	10.75	10.28	10.89	10.88	10.40	10.64	11.26	10.83	10.82	11.21	10.78
T_e	14.18	13.56	13.98	13.37	14.15	14.15	13.52	13.83	14.65	14.08	14.07	14.58	14.01

Table 6. Average Monthly significant wave height (m), significant wave height square (m^2), zero mean period (s), mean wave energy (s) for NDelt2

	Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
H_s	1.19	1.40	1.58	1.84	2.31	2.48	2.24	2.07	1.89	1.72	1.63	1.54	1.83
H_S^2	1.41	1.96	2.49	3.39	5.35	6.16	5.03	4.30	3.56	2.97	2.66	2.38	3.47
α	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
T_Z	9.93	10.09	10.46	9.81	10.56	10.54	9.99	10.32	10.97	10.43	10.30	10.54	10.33
T_e	12.91	13.12	13.60	12.77	13.72	13.71	12.98	13.41	14.26	13.56	13.39	13.70	13.43

Table 7. Average Monthly significant wave height (m), significant wave height square (m^2), zero mean period (s), mean wave energy (s) for NDelt3

	Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
H_s	1.14	1.31	1.48	1.75	2.18	2.43	2.19	2.01	1.83	1.63	1.53	1.49	1.75
H_S^2	1.28	1.70	2.20	3.04	4.76	5.89	4.79	4.02	3.35	2.67	2.33	2.23	3.19
α	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
T_Z	10.36	9.67	10.01	10.74	10.47	10.07	10.25	10.00	10.10	9.10	10.71	10.23	10.18
T_e	13.47	12.57	13.01	13.96	13.61	13.10	13.32	13.01	13.13	12.35	13.92	13.29	13.23

Fig 2(a) and Fig 3 (a) indicated the zero wave period and it corresponding mean wave period for NDelt1 station, the zero wave period is from 4 to 14 s with an average of 10.78 s while the mean wave period ranges from 5.1 to 18.2 s with an average value of 14.01 s. Fig 1(b) indicated the significant wave height of the NDelt2 station with it minimum value of 0.92 m and reaches its highest value of 3 m. In Fig 1(c), the least and highest values of significant wave height are 0.69 and 2.79 m respectively for NDelt3 station with the average of 1.75 m shown in Table 7. However, Fig 2 (b) shows that the zero-wave period was at its peak (14.23 s) and minimum (2.94s) for NDelt2 while Fig 3(b) are the corresponding mean wave periods which are 5.5 s and 15.3 s respectively. Table 6 shows that the average values for zero wave period and mean wave energy for the NDelt2 station as 10.33 and 13.43 s respectively. However, Table 7 shows the average values for both the zero wave period and mean wave energy for NDelt3 station within those periods was found to be 10.18 and 13.23 s respectively. Fig 2 (c) and Fig 3 (c) are the scale pictures of zero wave period and mean wave energy for NDelt3 station with the maximum values of 12.7 and 16.15 s while their minimum values are 7.34 and 9.54 s respectively.

3.2Wave Power Density and Energy

Fig. 4 shown the wave power in both the three locations experience a strongly fluctuations due to variations in their corresponding significant wave heights. However, Table 8 shows that the average wave power densities for NDelt1, NDelt2 and NDelt3 are 23.69, 25.71 and 23.13 kW/m respectively. Fig 5(a) shows that the wave power density attended it least value (10.51 kW/m) in the month of January, then increases significantly from February and attended it maximum value (43.61 kW/m) in June and decreases to maintain almost same height in August (28.91 kW/m) and September (28.93 kW/m) before further declining to its lowest values within December (11.12 kW/m) and January in along NDelt1 station.

However, the other two stations NDelt2 and NDelt3 displaced almost the same scenario (monthly variations) as that of NDelt1 station in which Fig 5(b) indicated minimum power density of 25.87 kW/m in January and maximum power density of 46.5 kW/m in June for NDelt2, the increment for the wave power density in Fig 5(b) occurred rapidly from January to June and decrease slowly from June to December (26.65 kW/m). Fig 5(c) indicates the monthly variability of the wave power density for NDelt3 at its highest peak within May (43.01 kW/m) and June (43.61 kW/m) with the lowest value of 9.64 kW/m happened in January. Table 9 shows the corresponding average wave energy densities for NDelt1, NDelt2 and NDelt3 to be 1954.18, 2196.35 and 2008.64 MWh/m respectively.

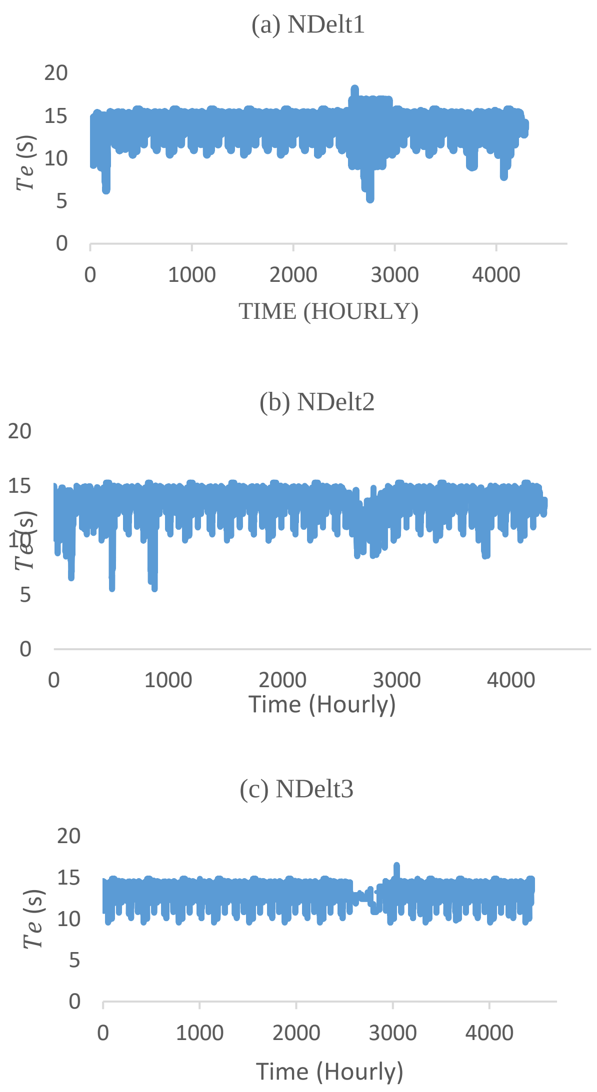


Fig 3: Original time-series of mean wave Energy between 2014 and 2023 for (a) NDelt1, (b) NDelt2 and (c) NDelt3

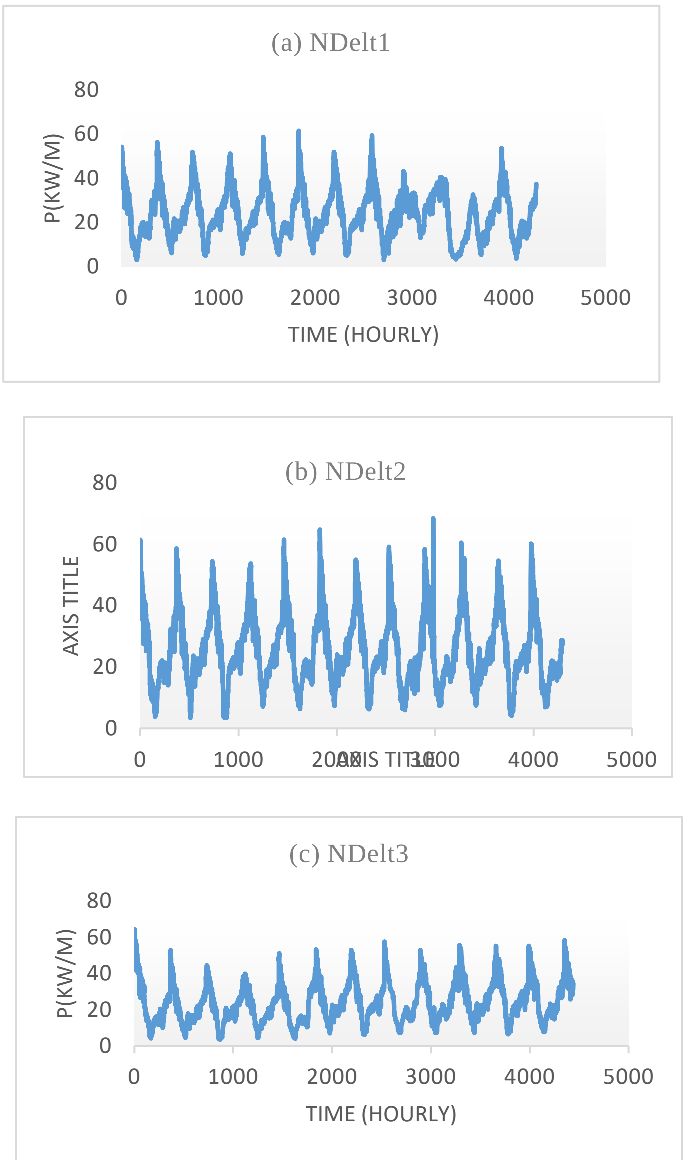


Fig 4: Original time-series of wave power density between 2013 to 2023 for (a) NDelt1, (b) NDelt2 and (c) NDelt3

Table 8: Monthly average wave power and energy density for NDelt1, NDelt2 and NDelt3

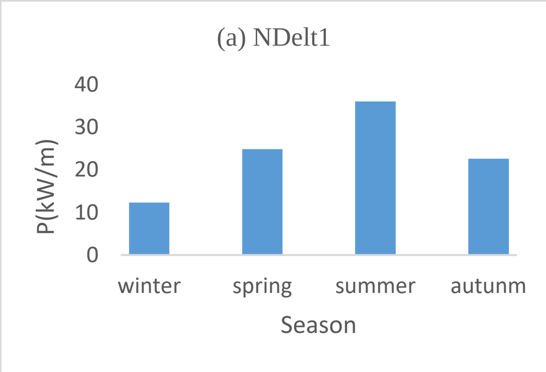
Months	NDelt1 Station		NDelt2 Station		NDelt3 Station	
	Power Density (kW/m)	Energy (MWh/m)	Power (kW/m)	Energy (MWh/m)	Power (kW/m)	Energy (MWh/m)
Jan	10.51	846.03	10.02	883.54	9.61	866.03
Feb	15.41	1258.74	14.16	1246.86	12.25	1072.99
Mar	19.69	1546.78	18.29	1568.94	16.16	1382.28
Apr	21.52	1837.64	23.81	2135.81	20.67	3002.41
May	33.29	2695.84	40.33	3411.51	34.79	3697.91
Jun	43.61	3522.25	46.45	3973.18	43.60	3009.21
Jul	35.64	3007.31	35.94	3153.04	33.12	2247.34
Aug	28.91	2389.27	31.70	2368.38	28.77	1679.23
Sep	28.94	2258.75	27.91	2583.91	25.64	1679.23
Oct	20.67	1679.85	22.16	1475.68	19.27	1917.40
Nov	18.18	1477.39	19.58	1671.64	16.66	1464.45
Dec	11.12	930.35	17.91	1883.77	17.11	1401.13
Mean	**23.96**	**1954.18**	**25.71**	**2196.35**	**23.13**	

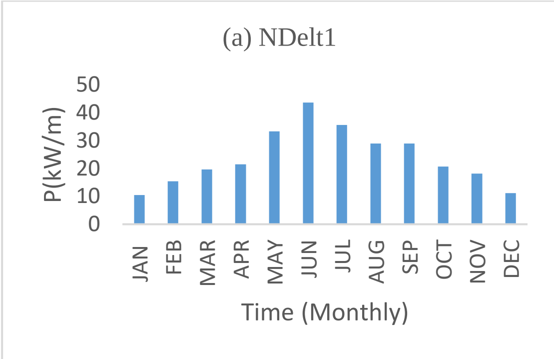
3.2.1 Seasonal Wave Power and Energy variability

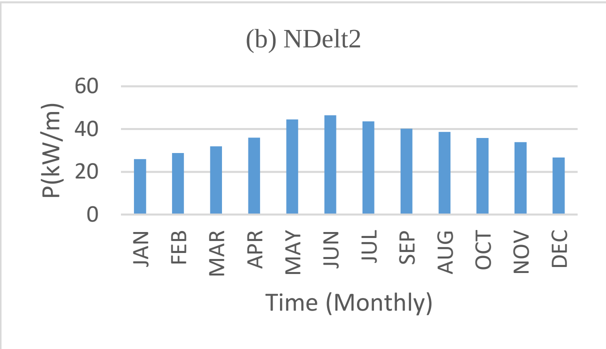
Fig 6(a) indicated the seasonal variation of the wave power density for NDelt1 station, the largest wave power density occurred in summer (36.01 kW/m) and least in winter (12.35 kW/m) while spring and autumns has the wave power density of 23.84 kW/m and 22.29 kW/m respectively. Fig 6(b) is the seasonal chart for NDelt2 station with wave power density of 27.1 kW/m in winter, 43.38 kW/m in summer, 37.51 kW/m in spring and 20.52 kW/m in autumns. The seasonal variability of wave power density for NDelt3 station has been indicated in Fig. 6(c) were the summer (35.16 kW/m) and spring (23.86 kW/m) has the highest values than during the winter (12.99 kW/m) and autumns (20.52 kW/m) season

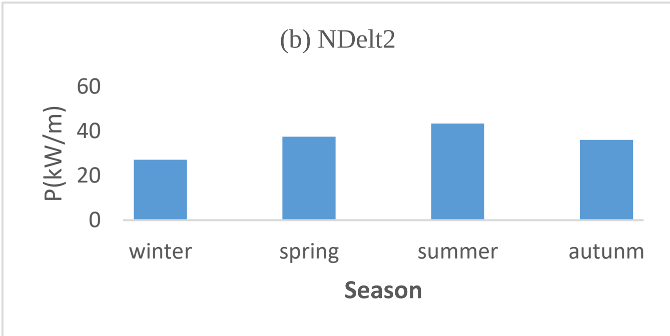
Wave energy resources in Delta state.

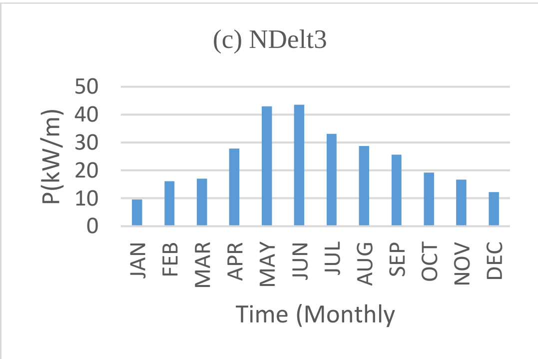
Adequate wave energy resources in a place played a significant role in setting up a wave power plant at reduced cost. The wave energy reserve pave way greater wave power assessment of a particular area [26]. when the wave energy reaches $p \geq 2$ kW/m in a specified area , then the power is said to be available and $P \geq 20$ kW/m shows that the resources is rich in the area [42, 30, 29]. Each of the NDelt1, NDelt2 and NDelt3 stations has shown in Table 17 to have wave energy density of above $P \geq 20$ kW/m, with the total wave power density for both NDelt1, NDelt2 and NDelt3 as 72.79 kW/m and wave energy density of 6159.17 MWh/m respectively. Thus, the research shows enormous resources to be available in those areas and will be enough to generate electricity for the nearby communities if appropriate wave energy converters were been installed











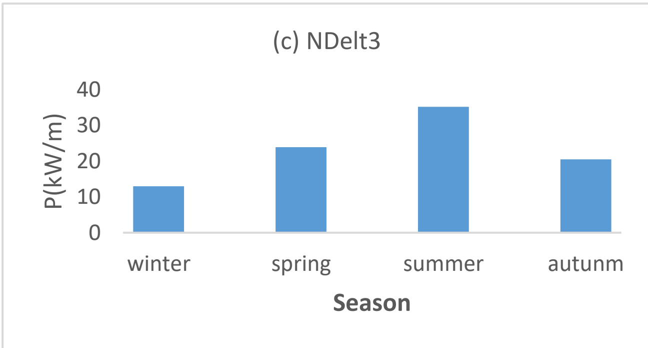


Fig 5.Monthly variations for wave power density for (a)NDelt1, (b) NDelt2 and (c) NDelt3

Fig 6. Seasonal variations for wave power (a)NDelt1, (b) NDelt2 and (c) NDelt3

Table 9: Total wave power and energy resources for NDelt1, NDelt2 and NDelt3

Points	**Average Power (KW/m)**	**Average Energy (MWh/m)**
NDelt1	23.96	1954.18
NDelt2	25.71	2196.35
NDelt3	23.13	2008.64
Total	**72.79**	**6159.17**

4. Conclusion

Wave power potentials for three locations on the sea water area of Delta state were been determined. The areas are NDelt1, NDelt2 and NDelt3 river bars. Ten years (2014 to 2023) significant wave heights and zero mean periods and directions data at the horizontal resolution of 0.5^0 X 0.5^0 with hourly temporal resolution and in GRIB file format data were been obtained from ERA5 of the European Council for Medium Range Weather Forecast (ECMWF).

The significant wave height data were been analyzed and the average values for NDelt1, NDelt2 and NDelt3 stations are 1.71, 1.83 and 1.75 m respectively. The mean wave energy was estimated using zero wave period obtained from ERA5 data and the average value of the mean wave energy for NDelt1 point is 14.01 s, NDelt2 is 13.43 s and NDelt3 is 13.23 s. The wave power density has also been estimated from the significant wave height and mean wave energy using deep water equation written in equation 7, this is because all the areas fall into deep water categories. However, the wave power densities for both locations attend their greatest values during summer and lowest during winter. During the summer period, the average wave power density for NDelt1 station is 36.01 kW/m, 43.38 kW/m for NDelt2 station and 35.16 kW/m for NDelt3 station. While NDelt1 station witnesses an average wave power density of 12.35 kW/m, NDelt2 (27.1 kW/m) and NDelt3 (12.99 kW/m) during winter period. The total average values for the wave power density for ten years (2014 to 2023) is found to be 23.96, 25.71 and 23.13 kW/m for NDelt1, NDelt2 and NDelt3 stations respectively. Thus, NDelt 2 displaced the highest wave power and energy resources as compared with that of the NDelt 1 and NDelt 3 respectively. Although, all the three points selected for the research shows that the wave power resource for electricity generation is available in the Delta state of Nigeria along the Gulf of Guinea.

4.1 Recommendation

Since only three locations were been considered in this work, more assessments are required to be carryout for different locations to discover more wave power resources in Nigeria. Work on the performances of the wave power energy and economic analysis for the areas should also put into considered in further research.

Acknowledge

The authors acknowledge the use of ECMWF ERA5 dataset which was found in (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-sinle-levels). The research was sponsored by the Tertiary Education Trust Fund (TETFUND) through Nigeria Maritime University Okerenkoko, Delta state of Nigeria. Thanks to the Nigerian Institute for Oceanography and Marine Research (NIOMR) for their supports.

Conflict of Interest

The authors in anyway have no conflict of interest with this work.

References

[1] Kwasi CC, Ighodaro OO. Performance Assessment of a Hydram Energy System on Varying Discharge Head for Power Generation. *Journal of the Nigerian Institution of Production Engineers (Ni.Prod.E)* 27(March 2023): 69-79

[2] Ighodaro OO, Egwaoje SO (2020) – Design and Feasibility Study of a PV-Micro Hydro Off-Grid Power Generating System. *Journal of Science and Technology Research*, 2(1): 213 -224

[3] Sharmita, N, (2023). Wave Energy; the renewable energy of the future: *Journal of Research in Humanities and Social Science*. *11*(2): 275 – 281. ISSN 2321-9467

[4] Okagbare GO, Omotehinse SA, Ighodaro OO (2022) – An Investigation of the Hydro-Power Potential of the Ojirami Dam in Nigeria. *Journal of Energy Technology and Environment* 4(1): 83 – 104.

[5] Viola, A., Trapanese, M., & Franzitta, V. (2013). Evaluation of the Potential Energy from Wave Motion on the Sicilian coast, *OCEANS - Bergen, MTS/IEEE*, 1–5, 10–14 June, Bergen, Norway.

[6] Falnes J, (2007). A review of wave energy extraction: *Marine Structures*, (20): 185–201.

[7] Osman, P., Behrens, S., Griffin, D., Hayward, J., Hemer, M., Knight, C., McGarry, S., & Wright, S. (2012). Ocean Renewable Energy: 2015–2050 An analysis of ocean renewable energy in Australia: CSIRO Energy Transformed and Wealth from Oceans Flagships, Melbourne.

[8] Smith, H., Haverson, D., & Smith, G. (2013) - A wave energy resource assessment case study: Review, analysis and lessons learnt', Renewable Energy, (60): 510 5 - 21.

[9] Cornett, A. (2008). A global wave energy resource assessment. In Proceedings of the 18th International Offshore

[10] López, I., Andreu, J., Ceballos, S., Martínez, A., I., & Kortabarria, I. (2013). Review of wave energy technologies and the necessary power-equipment; Renewable and Sustainable Energy Reviews, 27, 413-434

[11] Sierra, J.P., White, A., Mösso, C., & Mestres, M. (2017). Assessment of the intra-annual and inter-annual variability of the wave energy resource in the Bay of Biscay (France). Energy, 141, 853–868. [CrossRef]

[12] Sheng, W., Li, H. A. (2017). Method for Energy and Resource Assessment of Waves in Finite Water Depths: Energies 10, 640.

[13] Gunwoo, K., Weon M. J., Kwang, S. L., Kicheon, J. Myung, E. L. (2011). Offshore and nearshore wave energy assessment around the Korean Peninsula: Energy, 36(3), 1460-1469, ISSN 0360-5442,

[14] López, M., Veigas, M., Iglesias, G. (2015). On the wave energy resource of Peru: Energy Conversion and Management, 90, 34–40.

[15] Arena, F., Laface, V., Malara, G., Romolo, A., Viviano, A., Fiamma, V., Sannino, G., Carillo, A. (2015). Wave climate analysis for the design of wave energy harvesters in the Mediterranean Sea: Renew. Energy, 77, 125–141.

[16] Amir, D., Kiran, B., Ranganath, L., & Pradnya, D. (2022). Assessment of Wave Energy Potential along the Erosion Prone Coast at Ullal, Karnataka: Journal of Oceanography and Marine Research. *10*(3). 1000252.

[17] Wan, Y., Zhang, J., Mrng, J., Wang, J. A. (2015). wave energy resource assessment in the China's seas based on multi-satellite merged radar altimeter data: Acta Oceanologica Sinica. *34*(3):115–124.

[18] Arinaga, A., & Cheung, K., (2012). Atlas of global wave energy from 10 years of reanalysis and hindcast data: Renewable Energy, 39(5), 1–49.

[19] Rusu, L., Soares, C. (2012). Wave energy assessments in the Azores islands: Renewable Energy, 45, 18–396.

[20] Tolman, H. L., (2014). User manual and system documentation of WAVEWATCH III version 4.18, NOAA / NWS / NCEP / MMAB Technical Note. *16*(194), 45-54.

[21] Luca, L., Adriana, C., & Gianmaria, S., (2013). Wave energy resource assessment in the Mediterranean, the Italian perspective: Renewable Energy, *50*(9), 938-949, ISSN 0960-1481, http://dx.doi.org/10.1016/j.renene.2012.08.023.

[22] Michael, G., Hughes, E., & Andrew, D. (2010). Heap, National-scale wave energy resource assessment for Australia: Renewable Energy, *35*(8), 1783-1791, ISSN 0960-1481.

[23] Wilsnon, M., Antonio, S., Antonio, F., & Joaqum, F. (2017). Statistical Analysis of Wave Energy Resources Available for Conversion at Natural Caves of Cape-Verde Islands: International Journal of Renewable Energy Sources. *2*(3), ISSN: 2367-9123

[24] Magnus S., Mariana B., Marta G., & Guedes, C. (2023). Wave Energy Assessment for the Atlantic Coast of Morocco: Centre for Marine Technology and Ocean Engineering (CENTEC), *11*(11), 2159

[25] Guy, H., Basil, B., Mathias, A., Bernard, N., & Viano, I., (2018). Wave Energy Resources Assessment Offshore Benin from ERA Re-Analysis: Gulf of Guinea: Physical Science Internal Journal. *19*(4), 1 – 11. ISSN 2348-0130

[26] Agbakwuru, J., Ahamefula, A., & Akaawase, B. T. (2019). Statistical Wave Description of Forcados Offshore in Nigeria. FUPRE Journal of Scientific and Industrial Research *3*(3), ISSN: 2579-1184 (Print) ISSN: 2578-1129 (Online

[27] Agbakwuru, J., & Idubor, F., (2019). Characteristics and Potentials of Nigerian Atlantic. International Journal of Engineering and Management Research. *9*(3), 164.

[28] Alvan, I., & Charity, O., (2019). Effects of Some Meteorological Parameters on Visibility in the Niger Delta Region of Nigeria: Physical Science International Journal. *21*(1), 1-11. ISSN: 2348-0130

[29] Iglesias, G., & Carballo, R. (2011). Wave power for La Isla Bonita, Energy, 35, 5013–5021.

[30] Iglesias, G., & Carballo, R. (2010). Offshore and inshore wave energy assessment: Asturias (N Spain)', Energy, *35*(5), 1964–1972.

[31] Iglesias, G., & Carballo, R. (2011). Choosing the site for the first wave farm in a region: a case study in the Galician Southwest (Spain)', Energy, 36, 5525–5531. [6] 120

[32] Guillou, N. (2020). Estimating wave energy flux from significant wave height and peak period. Renew. Energy, 155, 1383–1393. [CrossRef] and Polar Engineering Conference, Vancouver, BC, Canada, 6–11 July 2008.

[33] Ren, J., Luo, Y., Chen, J., Zhang, X., & Zhong, Y. (2009). Research on wave power application by the information system for ocean wave resources evaluation. Renewable Energy. *27*(3), 93–97.

[34] Pierson, W. J., & Moskowitz, L. (1964) A proposed spectral form for fully developed wind seas based on the similarity theory of S.A. Kitaigorodskii', Journal of Geophysical Research, *69*(24), 5181–5190.

[35] Yang, C., Fan, Y. M., Lee, B. C., & Kao, C. C. (2011). Long-term Variability and Trends of Wave Climate in the Southern East China Sea and Northwestern Pacific Ocean from 1958 to 2009 – Wave Modeling Validation', Proceedings of the Twenty-first (2011) International Offshore and Polar Engineering Conference, Maui, Hawaii, USA, June 19-24.

[36] Ahn, S., Haas, K. A., & Neary, V.S. (2019). Wave energy resource classification system for US coastal waters. Renew. Sustain. Energy Rev. *104*, 54–68. [CrossRef]

[37] Ren, J., Luo, Y., Zhong, Y., & XU, Z. (2008). The implementation for the analysis system of ocean wave resources and the application of wave energy power generation. Journal of Zhejiang University of Technology. *36*(2):186–191.

[38] Muraleedharan, G., Lucas, C., & Guedes, C. S. (2023). Spectral wave energy period and peak period statistics concomitant with maximum significant wave heights. Coastal Engineering, *183*, 104260.

[39] Akinsanya A., Gudmestad, O.T., & Agbakwuru, J.A. (2017). The swell description of Bonga offshore Nigeria. Ocean system engineering. 20(4). Pp. 9-15. Techno press

[40] Gunn, K., & Stock-Williams, C., (2012). Quantifying the global wave power resource', Renewable Energy, *44*, 296–304.

[41] Eugen, R., & Guedes, SC. (2009). Numerical modeling to estimate the spartial distribution of the wave energy in the Portuguese near shore. Renew Energy. *34*, 1963-1975.

[42] Wang, C., & Lu, W. (2009). Analysis methods and reserves evaluation of ocean energy resources (in Chinese). Beijing: China Ocean Press, 61 – 62.

[43] Xinyu H., Yizhou, F., Yanan, W., He, W., & Hooi-Siang, K. (2023). An approach to assess the potential of wave energy resources based on directional energy flux: ScienceDirect, ELSEVIER, *287*(1), 115732.

[44] Holthuijsen, H. (2010). Waves in Oceanic and Coastal waters, Cambridge, Cambridge University Press, United Kingdom

[45] Holthuijsen, L. H., Booij, N., & Haagsma, I. J. G. (1998). Comparing 1st-, 2nd- and 3rd-generation coastal wave modelling, 26th International Conference of Coastal Engineering, Copenhagen, 140-149.

[46] Folley, M., Cornett, A., Holmes, B., Lenee-Bluhm, P., & Liria, P. (2012). Standardizing resource assessment for wave energy converters, 4th International Conference on Ocean Energy, Dublin 17–19 October.

[47] Kumar, K., & Anoop, T. (2015). Wave energy resource assessment for the Indian shelf seas', Renewable Energy, *76*, 212–219.