
Techno–Economic Viability of Ocean Wave Power Generation in the Bight of Benin, Southwest Nigerian Coast

Christian O. O. Okwori[1,*], Olawale S. Ismail[1], and Moses O. Petinrin[1,2], Andrew Ndubuisi Ochei[4]

[1]Department of Mechanical Engineering, Faculty of Technology, University of Ibadan

[2]School of Mechanical Engineering, Fiji National University, Suva, Fiji

Abstract

With about 40% of Nigeria's population representing over 92million and about 45% of Sub-Saharan Africa representing over 600million lacking access to electricity or clean energy, being the energy poverty capital of the world, developing autonomous renewable energy sources based on isolated or interconnected mini-grid systems is exigent. Ocean renewable energies like wave energy present a great option given the fact that coastal and cities tend to have higher populations, while islets, remote settlements, and swampy areas in Nigeria's littoral zones tend to be primarily underserved due to technical difficulty, logistic challenges, and cost of grid extension, among other things. The wave energy electric power generation potential for Southwest Nigeria was assessed by obtaining and averaging the significant wave heights (SWH), periods, and ancillary datasets at various times of the day and for three geolocations evenly spread from west to east across the region's coastline in the Bight of Benin. The data for wave energy variables were evaluated using various models and methods, including Techno-Economic Renewable Viability Index (TEREVI), conventional Levelized Cost of Electricity (LCOE), Techno-Economic Levelized Cost of Energy (TELCOE), and HOMER simulation to measure the techno-economic viability and general competitiveness among other proven and probable renewable energy resources in Southwest Nigeria based on a 100kW pilot wave power plant. From the results, HOMER optimization energy cost is \$0.094003211/kWh, the Matlab energy generation cost simulation is \$0.09t11/kWh, the LCOE value is \$0.082307404/kWh, and the TELCOE value is \$0.092809/kWh. Wave power potential in the Bight of Benin shows a conservative value of low to marginal commercial viability based on existing conversion technologies owing to low learning rate, thus presenting a medium to long-term electrification promise as a fair future sustainable energy strategy especially given Nigeria's drive towards blue economy, energy transition, and the trend towards low wave height conversion technologies that is likely going to increase with the advance in research and the development of high-efficiency wave turbines and site preparation techniques serving not just power generation but also integral to windbreaks for ports and harbours.

Keywords: wave power, significant wave height, wave period, renewable energy, Bight of Benin, marine energy resources, wave energy potential.

1.0. Introduction

Though unexplored despite inadequate electricity generation and the aim of the federal government to buoy the Nigeria's blue economy signalled by the recent establishment of a ministry for Blue Economy, wave energy and other marine energy resources especially renewables is strategic to the realization of over 90% of the Social Development Goals and other development targets at all levels of administration especially in the coastal sub Saharan African region.

Southwest Nigeria has a coastline of 275Km to 360Km bounding Lagos for 182Km, Ondo 70Km, and Ogun for 24Km in the Bight of Benin at the Gulf of Guinea in the Atlantic Ocean (Ssentongo 1986; Google Map 2023; LGI 2018; MEPB 2023; Nigerian Tribune, 2020) which presents a strategic advantage for multipurpose utilization in terms of power generation, transportation, fishing, tourism, and so on which could all be developed as an integrated model.

Inadequate electricity supply is at the top of Nigeria's socioeconomic challenges such that aside impeding the country's long targeted emergence as World Top 20 Economy, it has resulted in annual losses in Gross Domestic Product (GDP) of about $30billion per annum as well as keeping Nigeria outside the top 100 global Ease of Doing Business ranking among other things being that energy account for the lion share of overhead cost for businesses and households(Nasir, 2021).

Though the Presidency reported that the national grid meets just about 15% of the nation's energy power needs, only about 60% of Nigerians are connected to the national grid of which the average daily electricity supply is less than 40% and sometimes in low quality for use aside problems of energy theft due just about only 60% of supplied electricity being paid for, obsolete equipment, frequent grid collapses, vandalization of gas pipelines and electrical equipment, wrong siting of power plants and so on(Nasir, 2021; Okonkwo, 2023).

The lack of electricity supply accompanied by the rising cost of Automotive Gas Oil(Diesel), natural gas, and Premium Motor Spirit (petrol) has led to the folding up of thousands of factories, cottage industries, and small business in the last 25years in Nigeria resulting in huge unemployment rate of over 40%, import dependency and net negative trade balance, spiralling foreign exchange cost, massive brain drain, rising multi dimension poverty index (MPDI), and slow economic growth among several things tied to the need for clean, sustainable, and affordable power supply(Awodipe, 2023; Addeh, 2023; Egole, 2023).

Wave turbines have lifespan of well over 50years with minimal maintenance and zero security concerns compared to most conventional power generation technologies and fossil – fired plants whose durability do not exceed 20years aside high operational cost due to fuel, maintenance, security, frequent breakdowns, and safety concerns among other things that have been bedevilling Nigeria's power sector (Zhang et al, 2020).

It is noteworthy that wave power has near-zero operational carbon emission and is very cost-effective with comparable fossil power generation sources beyond 25 to 30years of operation since it normally outlives the latter by up to 100% or more. This makes it all the more likely a dominant energy source of the near future, even for regions whose marines have low to marginal potentials.

Due to the tendency for high human settlement rates in coastal areas, the development of wave energy conversion farms as well as other marine renewable energy resources will great engender embedded power system thereby grossly reducing or eliminating transmission cost, which is key to capital cost, sometime accounting for more than 50% of investment sum, and funding as well as project delivery time and security of power infrastructure.

This research is focused on wave power as part of an optimized hybrid energy configuration for distributed generation driving mini–grids in interoperable connections, standalone or island modes for the best cost-effective solutions in line with the United Nations, World Bank, and International Finance Corporation (IFC) strategy and Net Zero targets.

1.1. Objectives

1.1.1. Acquisition of wave energy data at the Bight of Benin, Nigerian coast
1.1.2. Design of a hypothetical wave-powered mini-grid system
1.1.3. Techno-economic evaluation of wave energy-powered mini-grid
1.1.4. Techno-economic viability determination of wave power mini-grid using Techno-Economic Renewable Energy Viability Index (TEREVI)

2.0. Literature Review

According to the Mean Wave Energy Potential Website (2022), wave energy potential in the Bight of Benin in the Benin Republic coastline is 7.5kW/m with a theoretical potential of about 8TWh/year, given the country's electricity consumption of 1.1TWh/annum and wave energy index of 36%. All this, given the fact that Benin

Republic's rural electrification rate is just 9% while its fossil, hydro, and other sources are about 88%, 9%, and 2% respectively. This points to a high possible impact of wave energy is applied to the country's energy solution, given the fact that the majority of its population is concentrated along the coastal areas.

Dahunsi and Foli (2023) carried out a past and future assessment of wave power index on the Gulf of Guinea using a 1979 – 2005 and 2006 – 2050 WAVEWATCH III simulated dataset, respectively. Their findings show a growing trend in wave power regime over time and are expected to double from 0.5kW/m to 1.0kW/m in 100years, which eventually makes wave energy a highly promising energy source for bottom-up electrification solutions in its bordering nations.

SEFA (2023) reported on ocean renewable energy in Africa for powering the emerging blue economy. The coast of West Africa is especially suitable for offshore wind, wave, and Ocean Thermal Energy Conversion (OTEC), which generally holds higher potential compared to offshore renewable energy resources. The wave energy and other offshore renewable energy resources are key to providing sustainable energy solutions for island nations and communities due to the high logistical cost of fuel transportation and medium to high population density, which represents the market.

Tulashie et al (2022) assessed the feasibility of wave power generation in Ghana by comparing the wave energy potential and existing power generation scenario in Ghana. The study concludes that the wave power potential of Ghana is even higher than the power potential for other sources of energy.

3.0. Wave Power Theories and Technologies

Wave Power is the generation of electricity from the motion of the water surface caused by prevailing windspeed as a result of differential heating between land and sea**.** Thus, the higher the windspeed over the water surface, the greater the disturbance and consequently the power potential because the wind transmits its kinetic energy to the water surface.

The windspeed determines the fetch, that is, the total distance of the wave travels as well as the period (time in seconds) it takes to complete it by which it reaches its maximum height called swell. This means that the key parameters for wave power evaluation are the wave height (significant wave height) and wave return period (time space between two successive waves) given that acceleration due to gravity is constant.

The higher the wave height and period, the higher the wave energy because potential energy increases with height, and the longer it takes for a successive wave to build up (arrive), the more energy it unleashes on the coastline. Note that seiche is not a tide but is actually the stationary wave generated and often spreads throughout the surface of small water bodies such as rivers and lakes.

As such, Wave power potential is highest in geographical coastal zones with high windspeed, mostly falling between latitudes 40 and 60 North and South. Global wave energy potential is estimated at 2TW (Gunn and Stock-Williams, 2012), with varying potentials across coastal countries. Imperatively, there are different types of waves and could occur in concurrence or interactively without necessarily being mutually exclusive as phenomena such as: deep water wave, transition (intermediate water) wave, shallow water wave, capillary wave, gravity wave, seiche, storm wave, standing wave, progressive wave, wind sea, tidal wave, swell wave, and Tsunami (Toffoli and Bitner – Gregersen, 2017).

Tidal waves are waves generated due to the gravitational pulls between the sun, the earth, and the moon, resulting in the movement of the ocean surface due to the resulting rise and fall of water depth. Ordinary tidal waves are generated by gravitational pulls and have a regime duration between 12 to 14hours and are restored by both Coriolis and gravitational forces. Transtidal waves are generated by gravitational pulls and have a regime less than 24hours duration and restored by both gravitational and Coriolis forces (Toffoli, 2017).

Long–period waves are generated by atmospheric pressure gradient and earthquakes with a regime between 5minutes and 12hours. Long–period waves are restored by gravitational forces (Kakinuma, 2019). Gravity waves are waves of periods between 1 to 20seconds generated by wind and whose velocity of propagation or travel depends on gravity, while infra-gravity waves are gravity waves of periods between 20 seconds and 5minutes generated by wind and atmospheric pressure gradients and whose frequency is less than the frequencies of water surface waves forced directly by wind. Both gravity waves and infra-gravity waves are restored by gravitational forces. Ultra-gravity waves are generated by wind with periods between 0.1 and 1s and are restored by surface tension and gravity (Rawat et al, 2014).

Capillary waves are waves propagated by wind of periods less than 0.1seconds and are restored by surface tension of the water. Wind seas are waves directly generated by local wind flow over the water surface, while swells are wind waves that have travelled beyond the generating water surface area and thus are milder than the wind sea (Zheng et al, 2015).

Storm waves are waves propagated by powerful shore winds or a drop in atmospheric pressure. A standing wave is a wave that is propagated in such a way that each point in the spatial axis of the wave has corresponding constant maximum and minimum amplitudes called nodes and anti-nodes, respectively. Seiche is a standing wave in completely or partially enclosed small or moderate water bodies such as rivers, lakes, etc., such that the wave is sometimes able to spread throughout the water surface.

A transition wave is a wave whose instantaneous value from point to point is independent of time and space. Deep water waves are waves in which the water depth is greater than half of the wavelength; thus, the bottom of the water has insignificant effect on the ocean surface wave while transition or intermediate water waves are waves propagated on water that is neither deep nor shallow water. Shallow water waves are waves propagated on waters whose depth-to-wavelength ratio is less than 1/20 which makes the surface waves to be affected by the seabed or bathymetry (Sheldon and Alcocer, 2022).

Where there is motion, there is energy and consequently power generation potential which can be harnessed in the cases of ocean wave by converting any of the 6 types of motions called 6 degree of freedom on a device on/in the water using buoys or oscillating columns or some form of linear generator among other possible conversion technologies called Power Take Off (PTO). 6 Degree of Freedom is sometimes referred to as 6DOF in the same sense as 3 Degree of Freedom (denoting Pitch, Yaw and Roll) is called 3DOF.

The 6 degrees of freedom or motions devices or objects such as buoys, floating platforms, ships, turbine blades, aircrafts etc. in fluids are subjected to includes 3 – dimensional linear motions along x, y, and z – axis with their respective 3 corresponding angular components owing to rotation change in direction: Heave, vertical up – down motion of a buoy or column in the water with its rotational component called Roll acting on the longitudinal axis; Surge, the horizontal back and forth motion of a buoy on the water surface with its rotational component called Pitch acting along the transverse axis; and Sway, the sideways left and right motion of the buoy on the water surface with its rotational component called Yaw acting along the normal axis concerning designed operational envelop for maneuverability which could be direct, semi – direct, indirect.

Fully Developed Sea (FDS) or Fully Developed Wave Form is a wave that has reached it maximum potential (height, H) and attained a steady–state energy balance of constant equilibrium by which its maximum speed (V_w) is now equal to that of the surface wind over its fetch at a given period, T. However, not every wave gets to attain the fully developed sea state, as the FDS phenomenon requires constant wind flow over the given surface stretch for a certain period.

Fetch (fetch length or wind fetch) is the horizontal distance of the water surface excited by a prevailing sea surface wind over a given time beyond which a wave's height does not increase. The higher the windspeed, the higher the fetch; and the fetch could be up to a maximum of about 1600Km (Heimduo, 2021) according to the Fetch Growth Law.

Fetch Growth Law states that the stationary limit(fetch) of a wave is proportional to the length of acceleration (the distance of the water body where the wind excites its surface) of the prevailing surface over a given distance, with wind speed and direction held constant.

Gravity waves are waves whose surface disturbances are restored to balance by gravitational force, resulting in a difference in height between the crest and trough. Capillary waves are waves generated between the liquid and gas(air) interface at the ocean surface, with the sine wave valley called a trough and the sine wave peak called a crest.

Significant Wave Height is the average value of the highest 1/3 wave heights measured on a water surface from trough to crest due to instantaneous variation in the properties of various waves (wave group) crossing a given spatial point at a time on the ocean surface. Significant wave height is the assumed mean wave height at fully developed sea used for wave energy evaluation.

Wave dispersion is the difference between wavelength and wave frequency due to differences in the various wave speeds in the same surface (plane) as various waves converge across the fetch. Wave energy has the highest power density of any renewable energy source and with a high capacity factor of about 90% (Clement et al, 2002). Wave power systems are classified based on power take-off system (PTO), location, and capacity.

Based on PTO, wave energy conversion system are currently based on 7 technologies using any of the following 3 fundamental operating principles: Oscillating Water Column (OWC), based on compressed air driven turbine system as a result of up and down motion of the water in sets of tubes or columns; Oscillating Water Drive(OWD), based on using the oscillatory motion of the water surface to drive hydro electric motors systems, linear generators and hydraulic turbines; and Overtopping Water Reservoir (OWR) system, based on using the wave height to capture water on a higher reservoir for running a low – head hydraulic turbine.

Common PTO technologies systems include the following 6 technologies: linear electric generator, based on a translational relative coil motion in magnetic field as opposed to the more common rotational electric generator that is based on rotational relative coil motion in a magnetic field; hydraulic ram system, based on back and forth motion of a plunger system as a result of the oscillatory motion of water surface; hydroelectric turbine, based on reservoir water head drive system; elastometric hose pump system; compressed air turbine system; and pump – to – shore system.

However, the 7 most practicable and technoeconomic Wave – to - Power technologies popularly applied for ocean wave energy conversion for power generation aside other existing and possible systems are: OWC, Point Absorber Buoys(PAB), OWR, Surface Attenuators Floater Hydraulic Converters(SAF), Floating In - Air Converters(FIA), and Submerged Pressure Differentials Membrane(SPD), Oscillating Wave Surge Converter (OWS). OWC conversion technology is based on the compression of air in a chamber (columns of tubes or channels) due to a rise in the wave height while the compressed air is forced through a narrow section optimized in dimensions to drive an air turbine, resulting in electric power generation. The fluid movement in the column and compressed air turbine operation generates quite some noise, which may be uncomfortable for marine life, aside possibility of small marine animals being trapped in the water columns.

PAB wave energy conversion technology uses a wave maker called point absorber, a very compact device much smaller than the oncoming ocean wavelength to absorb wave energy by radiating an opposing wave having destructive interference with the oncoming ocean wave resulting in swell and thus increased wave height for larger translational movement by the floater cabled to the seabed for more power generation typical by means of linear electric generator(alternator), linear – rotary converters, or hydraulic pump systems(Path Wave Energy Project, 2017). The PAB is a great way of optimizing wave energy potential per given wave space but best located offshore in order not to degrade the shoreline.

OWR wave energy conversion technology is based on taking advantage of the wave speed and height to feel water in a long structure constructed as a water reservoir much higher than the sea level such that the potential energy of the reservoir water is used to drive a low head hydroelectric power turbine. OWR may be constructed onshore, near shore or offshore.

SAF wave energy conversion technology is based on the principle of generating power via hydraulic pumps from wave swells created by the flexing motion of water surface due to multi - segmented floating devices connected to each other and oriented at right angles to the prevailing wave.

FIA wave energy conversion technology uses any of various techniques based on the heave motion of the ocean surface causing the expansion and contraction of an airbag ballasted in the water (Kurniawan et al, 2016). The variable volume air bag is connected to the generator for electricity production and due to its compressibility, FIA seems to hold great promises of retaining it harmonic motion much longer than would rigid bodies, thus generating more power. Due to their location above water, FIA has the lowest maintenance and operating expenditure due to ease of inspection, minimal contact with marine water, and technical simplicity.

OWS wave energy conversion technology generates electricity using the rise and fall of wave head by virtue of a buoy (e.g., membrane, float, or flap) anchored to the seabed or moored to a platform oscillating vertically at amplitudes based on the wave head within its operating envelope. OWC power output may be increased by incorporating a parabolic wave reflector in order to focus the oncoming waves to swell at the buoy, thus increasing its amplitude and consequently power output (JUSTIA, 2019; Wang et al, 2004). Figure 3.2 shows the OWC system as applied for the design of the hypothetical 100kW wave-powered hybrid mini-grid.

SPD wave power conversion technology works based on using the pressure gradient between 2 points below a wave to create flow that drives a turbine via a flexible membrane (flexible rubber or composite material) called submerged pressure differential converted (SPDC), which is the working surface between the water and the PTO. The system is usually installed at the seabed on at mid – waters well protect from the impact of sea water loads on the free surface while also ensuring a short distance from the free surface due to non–linear diminishing of wave load with distance from the free surface.

Based on location, wave power systems are grouped into: Shoreline Wave Power Plant, having water depth between 0 to 20m; Near Shore Wave Power Plant, having water depth from 20m to 40m; and Offshore Wave Power Plant, having water depth above 40m. Generally, the further offshore, the better for power output, but the higher the cost of installation and maintenance (Titah - Benbouzid and Benbouzid, 2015).

Nigeria has a coastline of 853Km with a Wave power potential in Nigeria is 7.5KW/m resulting in a wave energy applicability in the country's power mix at 12% with a coastal (Wave Energy Potential Website, 2021). Nigeria's highest tidal energy potential is 6.9m, which occurs at the Bite of Bonny (Ikwuaba, 2013) and thereabouts. Wave power is determined by the wave height, wavelength, wave period, fetch and the fully developed sea (Nwaokocha, 2013) as well as bathymetry and seafloor topography among other things (Kayode and Koya, 2019).

Among several notable wave power projects developed in recent time is the 62.5MW Victoria Wave Power Plant in Australia with a 600,00Volts output built by Lockheed Aerospace Corporation Technology as the Original Equipment Manufacturer based OWC piston converting translational to rotational motion of generators-based Ocean Power Technology (OPT) Mark-3 Buoys weighing 180T and having 866KW Peak each with underwater substation running underground cables to shore.

The Victoria Wave power project was rolled out in 3 phases, beginning with the 2.4MW phase-1 based on Mark-3 models with a projected life of 25 years, having zero environmental impact on the ocean and bird lives, with little noise. The landscape is 11.5meters high from arm's length and 1.6 meters high from the shoreline. The average wave power across the Nigerian coastal line of the Gulf of Guinea increases from the Eastern end (Bite of Bonny) at 5.64KW/m to the Western extreme (Bight of Benin) at 10.74KW/m with rainy(wet season) months higher than harmattan(dry season) months showing up 5% correlation between rainfall and wave power variations (Kayode and Koya, 2019).

Using advanced hybrid technologies and efficient systems, the wave power potentials of coastal stretches are likely to much more than currently envisages with southwest Nigeria standing a create chance at optimizing her wave energy opportunities at shoreline, near shore and offshore which is by current estimate at about 1.6GWh of electricity annually for Southwest Nigeria coastline in the Gulf of Guinea having a total stretch of 360Km.

Based on Holthuijsen (2007), the wave energy potential, flux or density along a coastal stretch per meter is given by:

$E_W = \frac{1}{16}\rho g^2 H^2$ …………………………3.1

According to Herbich (2000) wave power density for deep waters (water depth> half the wavelength) is determined by the following equation given the nominal wave height, H; acceleration due to gravity, g and wave return period, T thus:

$P_W = \frac{1}{64\Pi}\rho g^2 H^2 T$ ……………………..3.2

$P_W = 0.5H^2T$ …………………3.3

While the practically extractable power is based on the electrical and mechanical system conversion efficiencies given as ηG and ηT, respectively. Thus:

$P_W = \frac{1}{64\Pi}\rho g^2 H^2 T\eta_G\eta_T$ …………………3.4

$P_w = 0.5H^2T\eta_G\eta_T$ ………………..2.5

While Wave Power for shallow water is the product of the total wave energy and wave celerity:

$P_w = E_W V$ ……………….3.6

Wave power or energy flux is the mean wave energy transportation rate per unit width through a vertical plane parallel to the wave crest is proportional to the group velocity, V_G which in turn depends on the wave length and the wave period due to dispersion rotation, and is given by:

$P_w = E_W V_G$ ……………….3.7

V_G is the velocity at which a wave's overall envelope shape of its amplitude (modulation or envelope) travels (propagates) through space. Based on Hasselman et al (1988) and Planetcalc (2023) for FDS, we can take H as the maximum height with V being the prevailing sea surface wind speed, thus:

$H = \frac{\psi V^2}{g}$ …………….3.8

Where ψ is the fetch coefficient and is usually 0.27.

While time, T required concerning the speed V and horizontal distance, D to achieve the maximum wave potential (height) is given by:

$$T(V,D) = 77.23\frac{D^{0.67}}{V^{0.34}g^{0.33}} \qquad \text{……………3.9}$$

The wave height (significant wave height or maximum wave height) and distance at fully developed sea is given by the following expressions:

$$\frac{gH}{V^2} = 4.13\ X\ 10^{-2}\ X\ [\frac{gD}{V^2}]^{\frac{1}{2}} \qquad \text{……………..3.10}$$

$$H = 0.0413V\sqrt{\frac{D}{g}} \qquad \text{……………..3.11}$$

Also, the wave return period, T can be determined from the distance covered at full sea by the following relation:

$$\frac{gT}{V} = 0.751(\frac{gD}{V^2})^{\frac{1}{3}} \qquad \text{………………..3.12}$$

$$T = 0.751V^{\frac{1}{3}}g^{-\frac{2}{3}}D^{\frac{1}{3}} \qquad \text{………………3.13}$$

$$T = 0.751\sqrt[3]{\frac{VD}{g^2}} \qquad \text{……………3.14}$$

The coefficient of drag, C_D is the ratio of the square of the frictional velocity to the square of the windspeed at 10m, V_{10} height at fully developed sea

$$C_D = \frac{{V_f}^2}{{V_{10}}^2} = 0.011 + 0.00035V_{10} \qquad \text{…………….3.15}$$

At a fully developed sea:

$$\frac{gH}{V^2} = 211.50 \qquad \text{……………….3.16}$$

$$T = 239.80\frac{V_f}{g} \qquad \text{…………….3.17}$$

Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
Vol. 47 No. 03 (2026)

$$D = 0.00523\sqrt{V_f g T^3} \qquad \text{……………3.18}$$

Except for additional limitations in which the wave period cannot exceed the following value for a given depth, d:

$$T \approx 9.78\sqrt{\frac{d}{g}} \qquad \text{……………3.19}$$

By empirical evaluation based on trained observations, the significant wave height is defined as the average height of 1/3 of the highest waves:

$$H = \frac{1}{3n}\sum_1^n h_1 + h_2 + \cdots h_n \qquad \text{……………….3.20}$$

Noting that the H is only the most common maximum wave height, as there will always be higher and lower wave heights in reality. Based on 10m wave, for example, there is one 10.7m wave in every 10 waves; one 15.1m wave in every 100 waves, and one 18.6m wave in every 1000waves, and so on.

Wave Number, K, is the phase difference between waves in radians across points on a spatial plane at the same time per unit wavelength, λ, of given spatial periods of waves and crests.

$$K = \frac{2\Pi}{\lambda} \qquad \text{……………3.21}$$

The phase velocity, Ʊ given its angular speed, ω, also called crest velocity, is given by:

$$Ʊ = \frac{\omega}{K} \qquad \text{………… 3.22}$$

The wave period is given by:

$$T = \frac{2\Pi}{\omega} \qquad \text{………..3.23}$$

Dispersion Law states that wave frequency is proportional to the wave number given the distance between the liquid surface and the bottom, h:

$$\omega = f(k)$$

$$\omega^2 = gKTanh(Kh) \qquad \text{…………………3.24}$$

Based on the hyperbolic tangent curve,

Kh → 0, TanKh → ∞

Kh → ∞. Tanh (Kh) → 1

Knowing that Tanh(Π) = 0.996271 ≈ 1, we can say $Kh \geq \Pi$

For a water to be considered deep, its depth must be greater than or equal to its ocean wavelength

$$h \geq \frac{1}{2}\lambda \rightarrow \frac{2\Pi h}{\lambda} \geq \Pi$$

With fairly accurate measurement of an ocean's wave period (T), the phase velocity (V), group velocity (V_G) and wavelength can be quickly determined by simply use of a stopwatch to time the flow of the wave crest/trough past a given point on its path where special equipment or wave tracking devices are not available.

It is necessary to determine the water depth in terms of shallow, transitional, and deep-water classification which can be fairly determined by judging based on water sizes or like using deep water formulas for ocean and so on where water depth is not a (necessary)parameter while more accurate computations can be carried out using numerical iteration to achieve functional value convergence. A wave is generated by sea breeze flow over the ocean surface, transmitting its energy to the water by travelling at a speed or rate that is greater than or equal to the phase velocity(V) of the wave in a given direction. Thus, at a fully developed sea, the wave reaches an equilibrium travel rate such that it generates as much energy as is transmitted to it. Figures 3.1, 3.3, 3.4, and 3.5 show the aerial scan of the Bight of Benin in the Gulf of Guinea, the tidal power viability assessment workflow, wave hybrid power mini-grid systems schematic, the bottom-up interconnected hybrid mini-grid cluster, and OWC wave energy conversion powertrain.

Following mathematical expressions of wave theory concerning water depths and metocean peculiarities by the World Meteorological Organization (WMO) from Lainge(1998) and Magnusson and Reistad(1998) as well as (FSF, 2003 and Planetcalc, 2015) based on hyperbolic curve, we can classify waves based on water depth using the depth to wavelength ratio thus:

I. Shallow Water:

$$Tanh(Kd) = Kd \qquad \text{………………….3.25}$$

$$h \leq \frac{1}{20}\lambda$$

thus

$$\omega^2 = gk(kh) = gk^2h \qquad \text{……………….3.26}$$

Since for shallow water wave dispersion is not necessary, hence phase velocity is independent of frequency for shallow water, while taking cognizance of the fact that non–linear effects may suffice when the wave's amplitude becomes proximal or comparable to the ocean wavelength, typically characterized by the visible fractures on top of the wave. Thus:

$$V = \sqrt{gh} = V_G = Group\ Velocity\ of\ Shallow\ Water \quad \ldots\ldots\ldots\ldots 3.27$$

$$\lambda = T\sqrt{gh} \quad \ldots\ldots\ldots\ldots 3.28$$

ii. Transitional Depth

$$Tanh(Kd) = Tanh(Kd)$$

$$\frac{1}{20}\lambda \leq \frac{h}{2} \leq \frac{1}{2}\lambda$$

$$V = \frac{gT}{2\Pi} Tanh[\frac{2\Pi d}{\lambda}] \quad \ldots\ldots\ldots\ldots 3.29$$

$$\lambda = \frac{gT^2}{2\Pi} Tanh[\frac{2\Pi d}{\lambda}] \quad \ldots\ldots\ldots\ldots 3.30$$

$$V_G = \frac{1}{2}\left[1 + \frac{\frac{4\Pi d}{\lambda}}{Sinh\frac{4\Pi d}{\lambda}}\right]V \quad \ldots\ldots\ldots 3.31$$

iii. Deep Waters:

$$Tanh(Kd) \approx 1$$

$$h \geq \frac{1}{2}\lambda$$

$$\omega^2 = gK \quad \ldots\ldots\ldots\ldots 3.32$$

$$V = \frac{gT}{2\Pi} \quad \ldots\ldots\ldots\ldots 3.33$$

$$\lambda = \frac{gT^2}{2\Pi} \quad \ldots\ldots\ldots\ldots 3.34$$

$$V_G = \frac{1}{2}V = \frac{gT}{4\Pi} \qquad \text{.................3.35}$$

Fig. 3.1: Bight of Benin in the Gulf of Guinea

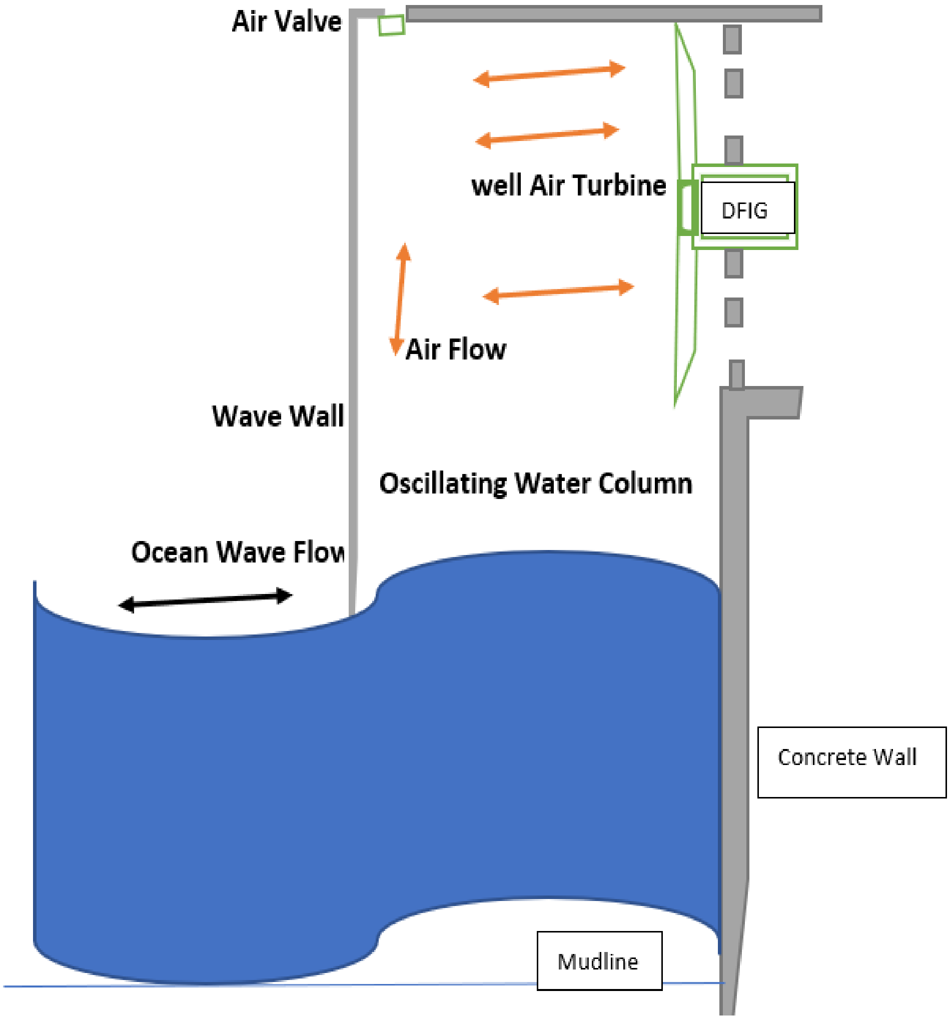

Fig. 3.2: schematic of the OWC wave energy conversion system

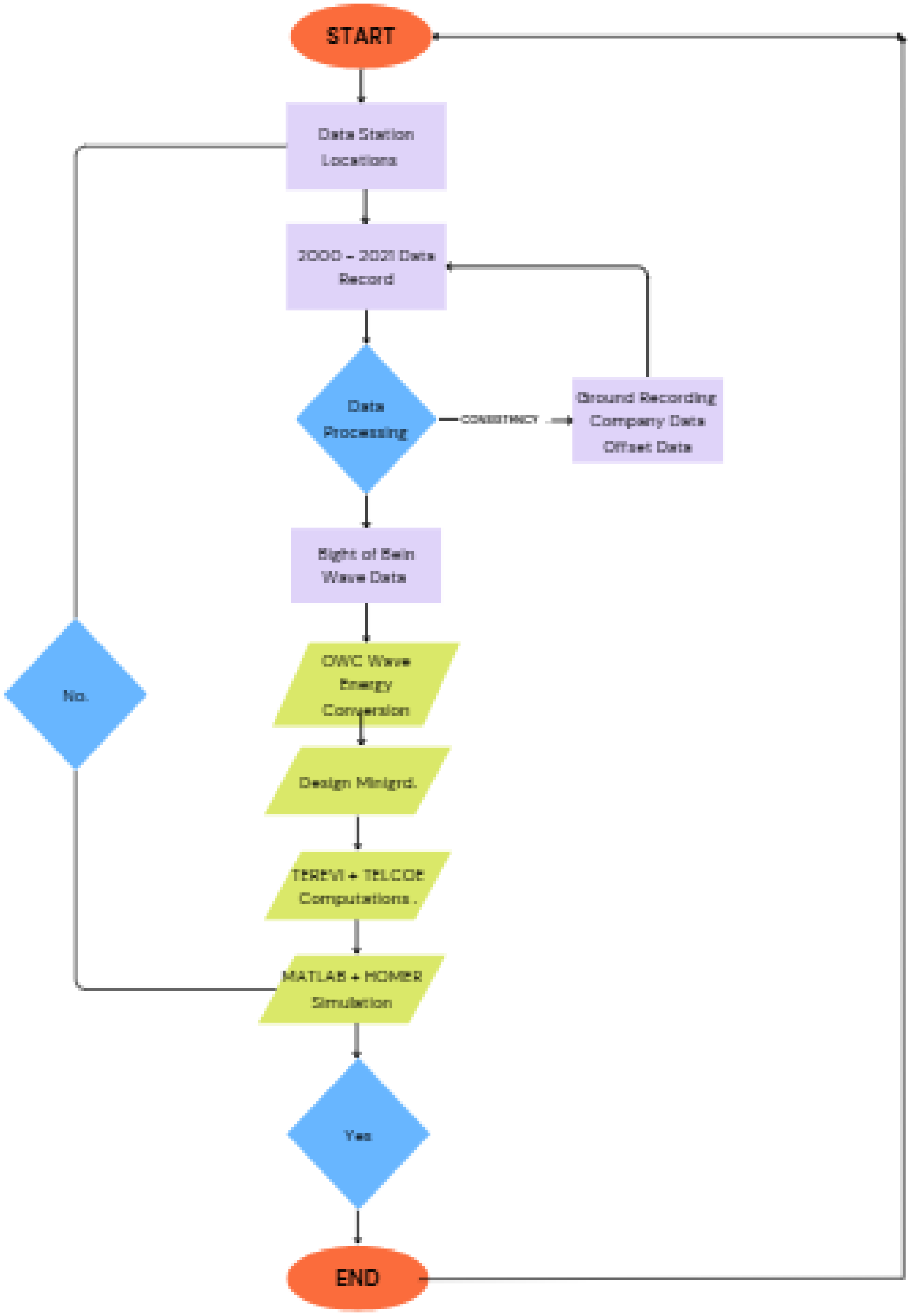

Fig. 3.3: wave energy **viability** study process flow diagram

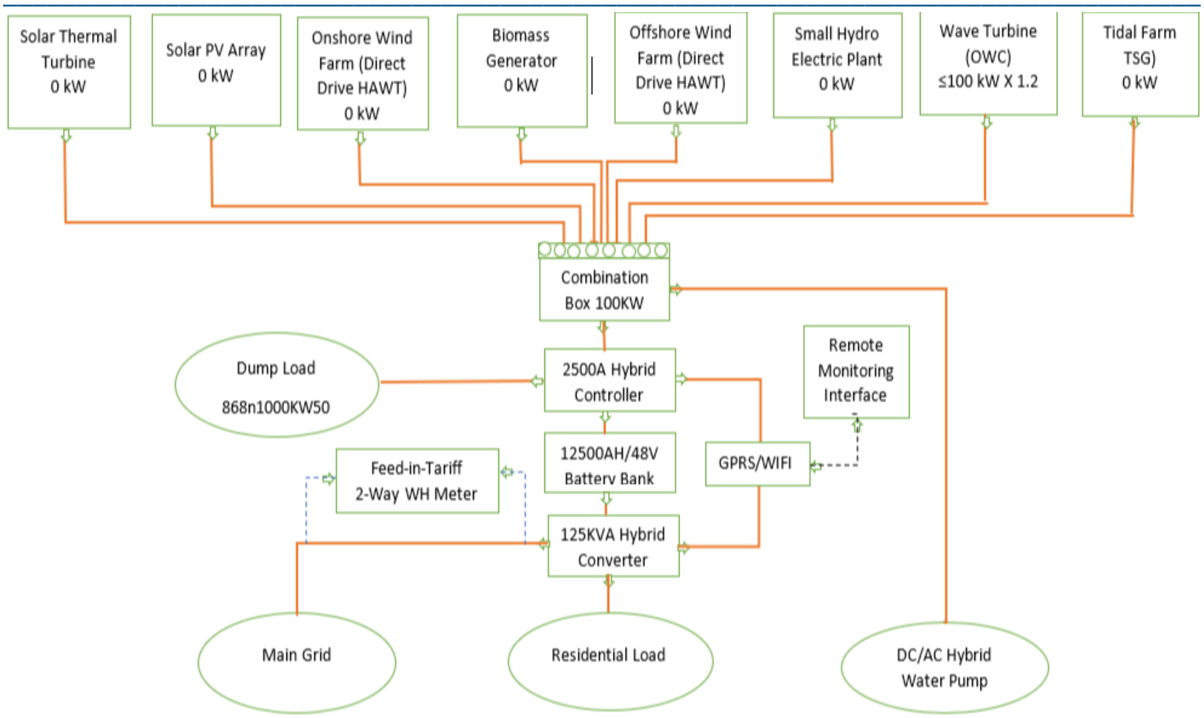

Fig. 3.4: Concept and schematic design of the hypothetical wave power plant in hybrid configuration

Fig. 3.5: Bottom-up mini-grid autonomous renewable energy hybrid power generation scheme

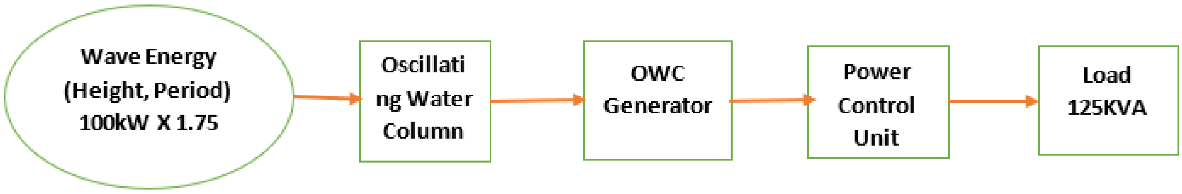

Fig. 3.6: wave energy conversion powertrain

4.0. Wave Data and Results

Aside from harnessing ocean energy resources, metocean data such as significant wave heights, wave period, swells, surface windspeed, tidal heights and so on are very important information for the location, design, construction, siting, and operation of shoreline and offshore facilities and activities such as oil production platforms, marine aviation, sea ports, jetties, navigation, defense systems, fishing, shipping, disaster management, and the determination of blue economic potentials among other things.

Significant wave heights can be obtained via several technologies and techniques including : satellite radar altimeters (SRA), pressure cells, step gauges, pitch and roll buoys, capacity wires, and some more of which SRA is the most accurate, reliable for recording wave data at single, multiple, and multi – temporal synoptic wave field viewpoints at comparatively lesser costs compared to the orthodox in – situ point data measurement and recording methods(Ojigi et al, 2022).

It is important to highlight the Various wave regimes determined by wave heights differentials as classified in Table 3.5 in order to have a simplified perspective of the energy potentials for power generation, much like the case of the Beaufort Scale for wind energy. Tables 4.1, 4.2, 4.3, 4.4, 4.5, 4.6, and 4.7 show the various wave data as part of the metocean information of the Bight of Benin as a sector of the Gulf of Guinea at large. This information primarily determines the suitability and viability of wave power generation.

Wave Power is the generation of electricity from the motion of the water surface caused by prevailing windspeed as a result of differential heating between land and sea. Thus, the higher the windspeed over the water surface, the greater the disturbance and consequently the power potential because the wind transmits its kinetic energy to the water surface.

The windspeed determines the fetch, that is the total distance of the wave travel as well as the period (time in seconds) it takes to complete it by which it reaches its maximum height called swell. This means that the key parameters for wave power evaluation are the wave height (significant wave height) and wave return period (time space between two successive waves) given that acceleration due to gravity is constant.

The higher the wave height and period, the higher the wave energy due to the fact that potential energy increases with height and the longer it takes for a successive wave to build – up (arrive), the more energy it unleashes on the coast line. Note that seiche is not a tide but is actually the stationary wave generated and often spread throughout the surface of small water bodies such as rivers and lakes.

32As such, Wave power potential is highest in geographical coastal zones with high windspeed mostly falling between Latitude 40 and 60 North and South. Global wave energy potential is estimated at 2TW (Gunn and Stock - Williams, 2012) with varying potentials across coastal countries.

Imperatively, there are different types of waves and could occur in concurrence or interactively without necessarily being mutually exclusive as phenomena such as : deep water wave, transition(intermediate water) wave, shallow water wave, capillary wave, gravity wave, seiche, storm wave, standing wave, progressive wave, wind sea, tidal wave, swell wave, and Tsunami(Toffoli and Bitner – Gregersen, 2017).

Tidal waves are waves generated due to the gravitational pulls between the sun, the earth, and the moon, resulting in the movement of the ocean surface due to the resulting rise and fall of water depth. Ordinary tidal waves are generated by gravitational pulls and have regime duration between 12 and 14hours and are restored by both Coriolis and gravitational forces. Transtidal wave are generated by gravitational pulls and have a regime less than 24hours duration and are restored by both gravitational and Coriolis forces.

Long–period waves are generated by atmospheric pressure gradient and earthquakes with a regime between 5minutes and 12hours. Long–period waves are restored by gravitational forces. Gravity waves are waves of periods between 1 and 20 20seconds generated by wind and whose velocity of propagation or travel depends on gravity, while infra-gravity waves are gravity waves of periods between 20 seconds and 5minutes generated by wind and atmospheric pressure gradients and whose frequency is less than the frequencies of water surface waves forced directly by wind. Both gravity waves and infra-gravity waves are restored by gravitational forces. Ultra-gravity waves are generated by wind with periods between 0. 1 and 1second and are restored by surface tension and gravity.

Capillary waves are waves propagated by wind of periods less than 0.1seconds and are restored by surface tension of the water. Wind seas are waves directly generated by local wind flow over water surface while swell are wind waves that have travelled beyond the generating water surface area and thus milder than the wind sea.

Storm waves are waves propagated by powerful shore winds or drop in atmospheric pressures. A standing wave is a wave that is propagated in such a way that each point in the spatial axis of the wave travel has corresponding constant maximum and minimum amplitudes called nodes and anti-nodes respectively. Seiche is a standing wave in completely or partially enclosed small or moderated water bodies such as rivers, lakes etc. such that the wave is sometime able spread throughout the water surface.

Transition wave is a wave whose instantaneous value from point to point is independent of time space. Deep water waves are waves in which the water depth is greater than half of the wavelength thus the bottom of water has insignificant effect on the ocean surface wave while transition or intermediate water waves are waves propagated on water that is neither deep nor shallow water. Shallow waters waves are waves propagated on waters whose depth to wavelength ratio is less than 1/20.

Where there is motion, there is energy and consequently power generation potential which can be harnessed in the cases of ocean wave by converting any of the 6 types of motions called 6 degree of freedom on a device on/in the water using buoys or oscillating columns or some form of linear generator among other possible conversion technologies called Power Take Off (PTO). 6 Degree of Freedom is sometimes referred to as 6DOF in the same sense as 3 Degree of Freedom (denoting Pitch, Yaw and Roll) is called 3DOF.

The 6 degrees of freedom or motions devices or objects such as buoys, floating platforms, ships, turbine blades, aircrafts etc. in fluids are subjected to includes 3 – dimensional linear motions along x, y, and z – axis with their respective 3 corresponding angular components owing to rotation change in direction: Heave, vertical up – down motion of a buoy or column in the water with its rotational component called Roll acting on the longitudinal axis ; Surge, the horizontal back and forth motion of a buoy on the water surface with its rotational component called Pitch acting along the transverse axis; and Sway, the sideways left and right motion of the buoy on the water surface with its rotational component called Yaw acting along the normal axis with respect to designed operational envelop for maneuverability which could be direct, semi – direct, indirect.

Fully Developed Sea (FDS) or Fully Developed Wave Form is a wave that has reached it maximum potential (height, H) and attained a steady – state energy balance of constant equilibrium by which its maximum speed (Vw) is now equal to that of the surface wind over its fetch at a given period, T. However, not every wave gets to attain the fully developed sea state as the FDS phenomena requires constant wind flow over the given surface stretch for certain period of time.

Fetch (fetch length or wind fetch) is the horizontal distance of water surface excited by a prevailing sea surface wind over a given time beyond which a wave's height does not increase. The higher the windspeed, the higher fetch; and fetch could be up to a maximum of about 1600Km (Heimduo, 2021) according to the Fetch Growth Law.

Fetch Growth Law states that the stationary limit(fetch) of a wave is proportional to the length of acceleration (the distance of the water body where the wind excites its surface) of the prevailing surface over a given distance with wind speed and direction held constant.

Gravity wave are waving whose surface disturbances are restored to balance by gravitational force making the difference in height between the crest and trough. Capillary waves are waves generated between liquid and gas(air) interface at the ocean surface with the sine wave valley called trough and the sine wave peak called crest.

Significant Wave Height is the average value of the highest 1/3 wave heights measured on a water surface from trough to crest due to instantaneous variation in the properties of various waves (wave group) crossing a given spatial point at a time on the ocean surface. Significant wave height is the assumed mean wave height at fully developed sea used for wave energy evaluation.

Wave dispersion is the difference between wavelength and wave frequency due to difference in the various wave speeds in the same surface (plane) as various waves converge across the fetch. Wave energy has the highest power density of any renewable energy source and with a high capacity factor of about 90% (Clement et al, 2002). Wave power systems are classified based on power take off system (PTO), location, and capacity.

Based on PTO, wave energy conversion system are currently based on 7 technologies using any of the following 3 fundamental operating principles : Oscillating Water Column (OWC), based on compressed air driven turbine system as a result of up and down motion of the water in sets of tubes or columns; Oscillating Water Drive(OWD), based on using the oscillatory motion of the water surface to drive hydro electric motors systems, linear generators and hydraulic turbines; and Overtopping Water Reservoir (OWR) system, based on using the wave height to capture water on a higher reservoir for running a low – head hydraulic turbine.

Common PTO technologies systems include the following 6 technologies : linear electric generator, based on a translational relative coil motion in magnetic field as opposed to the more common rotational electric generator that is based on rotational relative coil motion in a magnetic field; hydraulic ram system, based on back and forth motion of a plunger system as a result of the oscillatory motion of water surface; hydroelectric turbine, based on reservoir water head drive system; elastomeric hose pump system; compressed air turbine system; and pump – to – shore system.

However, the 7 most practicable and technoeconomic Wave – to - Power technologies popularly applied for ocean wave energy conversion for power generation aside other existing and possible systems are: OWC, Point Absorber Buoys (PAB), OWR, Surface Attenuators Floater Hydraulic Converters (SAF), Floating In - Air Converters (FIA), and Submerged Pressure Differentials Membrane (SPD), Oscillating Wave Surge Converter (OWS).

OWC conversion technology is based on the compression of air in a chamber (columns of tubes or channels) due to rise in the wave height while the compressed air is forced through a narrow section optimized in dimensions to drive an air turbine resulting in electric power generation. The fluid movement in the column and compressed air turbine operation generates quite some noise which may be uncomfortable for marine life aside possibility of small marine animals being trapped in the water columns.

PAB wave energy conversion technology uses a wave maker called point absorber, a very compact device much smaller than the oncoming ocean wavelength to absorb wave energy by radiating an opposing wave having destructive interference with the oncoming ocean wave resulting in swell and thus increased wave height for larger translational movement by the floater cabled to the seabed for more power generation typical by means of linear electric generator(alternator), linear – rotary converters, or hydraulic pump systems(Path Wave Energy Project, 2017). The PAB is a great way of optimizing wave energy potential per given wave space but best located offshore in order not to degrade the shoreline.

OWR wave energy conversion technology is based on taking advantage of the wave speed and height to feel water in a long structure constructed as a water reservoir much higher than the sea level such that the potential energy of the reservoir water is used to drive a low head hydroelectric power turbine. OWR may be constructed onshore, near shore or offshore.

SAF wave energy conversion technology is based on the principle of generating power via hydraulic pumps from wave swells created by the flexing motion of water surface due to multi - segmented floating devices connected to each other and oriented at right angles to the prevailing wave.

FIA wave energy conversion technology uses any of various techniques based on the heave motion of the ocean surface causing the expansion and contraction of an airbag ballasted in the water (Kurniawan et al, 2016). The variable volume air bag is connected to the generator for electricity production and due to its compressibility, FIA seems to hold great promises of retaining it harmonic motion much longer than would rigid bodies thus generating more powers. Due to their location above water, FIA have the lowest maintenance and operating expenditure due to ease of inspection, minimal contact with marine water and technical simplicity.

OWS wave energy conversion technology generates electricity using the rise and fall of wave head by virtue of a buoy (e.g., membrane, float, or flap) anchored to the seabed or moored to a platform oscillating vertically at amplitudes based on the wave head within its operating envelope. OWC power output may be increased by incorporating a parabolic wave reflector in order to focus the oncoming waves to swell at the buoy thus increasing its amplitude and consequently power output (JUSTIA, 2019; Wang et al, 2004).

SPD wave power conversion technology works based on using the pressure gradient between 2 points below a wave to create flow that drives a turbine via a flexible membrane (flexible rubber or composite material) called submerged pressure differential converted (SPDC) which is the working surface between the water and the PTO. The system is usually installed at seabed on at mid – waters well protect from the impact of sea water loads on the free surface while also ensuring not much distance from the free surface due to non – linear diminishing of wave load with distance from the free surface.

Based on location, wave power systems are grouped into: Shoreline Wave Power Plant, having water depth between 0 to 20m; Near Shore Wave Power Plant, having water depth from 20m to 40m; and Offshore Wave Power Plant, having water depth above 40m. Generally, the further offshore, the better for power output but the higher the cost of installation and maintenance (Titah - Benbouzid and Benbouzid, 2015).

Nigeria has a coastline of 853Km with a Wave power potential in Nigeria is 7.5KW/m resulting in a wave energy applicability in the country's power mix at 12% with a coastal (Wave Energy Potential Website, 2021). Nigeria's highest tidal energy potential is 6.9m, which occurs at the Bite of Bonny (Ikwuaba, 2013) and thereabouts. Wave power is determined by the wave height, wavelength, wave period, fetch, and the fully developed sea (Nwaokocha, 2013) as well as bathymetry and seafloor topography, among other things (Kayode and Koya, 2019).

Among several notable wave power projects developed in recent time is the 62.5MW Victoria Wave Power Plant in Australia with a 600,00Volts output built by Lockheed Aerospace Corporation Technology as the Original Equipment Manufacturer based OWC piston converting translational to rotational motion of generators-based Ocean Power Technology (OPT) Mark-3 Buoys weighing 180T and having 866KW Peak each with underwater substation running underground cables to shore. The Victoria Wave power project was rollout is in 3 phases, beginning with the 2.4MW phase-1 based on Mark-3 models with a projected life of 25 years, having zero environmental impact on ocean and bird lives with little noise. The landscape is 11.5meters high from arm's length and 1.6mm high from shoreline. The average wave power across the Nigerian coastal line of the Gulf of Guinea increases from the Eastern end (Bite of Bonny) at 5.64KW/m to the Western extreme (Bight of Benin) at 10.74KW/m with rainy (wet season) months higher than harmattan (dry season) months showing up 5% correlation between rainfall and wave power variations (Kayode and Koya, 2019).

Using advanced hybrid technologies and efficient systems, the wave power potentials of coastal stretches are likely to much more than currently envisages with southwest Nigeria standing a create chance at optimizing her wave energy opportunities at shoreline, near shore and offshore which is by current estimate at about 1.6GWh of electricity annually for Southwest Nigeria coastline in the Gulf of Guinea having a total stretch of 360Km.

Aside from harnessing ocean energy resources, metocean data such as significant wave heights, wave period, swells, surface windspeed, tidal heights and so on are very important information for the location, design, construction, siting, and operation of shoreline and offshore facilities and activities such as oil production platforms, marine aviation, sea ports, jetties, navigation, defense systems, fishing, shipping, disaster management, and the determination of blue economic potentials among other things.

Significant wave heights can be obtained via several technologies and techniques including: satellite radar altimeters (SRA), pressure cells, step gauges, pitch and roll buoys, capacity wires, and some more of which SRA is the most accurate, reliable for recording wave data at single, multiple, and multi – temporal synoptic wave field viewpoints at comparatively lesser costs compared to the orthodox in – situ point data measurement and recording methods(Ojigi et al, 2022).

Based on results from near real-time SRA data estimates of some selected Nigerian coastal fronts obtained by Ojigi et al(2022) between 2009 and 2017, the average significant wave heights for three stations in Lagos are NNS Beecroft, 1.286m; Takwa Bay, 1.287m; and UWWS, 1.288m while FOB – E in and Forcados in Delta State are 1.29m and 1.256m respectively with Bayelsa's ABB recording 1.249m which similar to tidal heights general indicates marginal wave energy potentials with significant wave height ranging between 0.78m and 3.21m and periods 4.8s and 20.4s with near – shore waves being greatly influenced by bathymetric topography(Koutitonsky, et al, 2011) which is corroborated by the 2020 GMES and Africa Monthly Physical Oceanography Bulletin on East Atlantic which puts the significant wave height in the eastern Atlantic coast covering Nigeria, Benin, Togo and Ghana at 0.57m to 3.35m in August.

Generally, wave, tidal, and other ocean renewable energy resources are more expensive compared to fossil fired power plants and land based energy power generation plants due to being relatively new technologies and the challenging nature of marine environments which typically require higher levels of technical skills, material quality, regulatory conditions, environmental, security, and safety considerations among other things whose cost are however bound to reduce with time given more familiarity, advances in research and development, and wider adoption globally.

According to a 2015 report by the National Ocean Economics Program (NOEP) by the Middlebury Institute for International Studies at Monterey Center for the Blue Economy, the levelized cost of electricity for ocean renewable energy technologies is 0.12$/KWh – 0.2$/KWH with capital cost of $4.8/W to $5/W given average capacity factor between 35% and 55%, for offshore wind power; 0.32$/KWh – $0.65/KWh with capital cost of $4.8/W – $5.8/W given average capacity factor between 25% and 40%, for wave power; $0.2/KWh – $0.58/KWh with capital cost of $0.5/W – $1/W given capacity factor between 25% and 55% , for tidal power; and $0.08/KWh – $0.68/KWh with capital cost of $25/W - $37/W given average capacity factor between 92% and 98%, for Ocean Thermal Energy Conversion (OTEC) power system.

The higher a renewable energy potential in a given geographical location such as wave height, period, tidal range, thermal gradient and so on, the cheaper the cost of electricity and the more justified and easier the funding and harnessing of such resources will be. Hence, with fast pace in renewable energy investment and research, prices of modules and LCOE has dropped significantly in the last 10years with further drops imminent in the next few years though with wide variations across geographical locations.

Wave Height and wave period occurrence proportion in Nigerian offshore based on data Ojigi et al (2022), Koutitonsky et al (2011), Wavewatch 3, Wave Forecast.com and various data collection sources are presented in the following table.

Wave height (m)	% Occurrence
0.5 – 1.0	8.6
1 – 1.5	49.8

1.5 – 2.0	32.5
2.0 – 2.5	7.1
2.5 – 3.0	0.9
3.0 – 3.5	0.9

Table 4.1: Mean Wave Height regime in the Bight of Benin

Wave Period (s)	% Occurrence
0 – 5	0
5 – 8	1.1
8 – 10	6.8
10 – 12	371
12 – 14	328
14 – 16	160
16 – 18	49
18 – 22	12

Table 4.2: Mean Wave Period regime in the Bight of Benin

The wave and tidal energy data for this study are based on results of real – time, archive and forecast data from Copernicus Marine Services, Nigerian Navy Hydrography Office, NASA – Langley Earth Data, Tidal – Forecast.com, Surface – Forecast.com, offshore oil producing companies, and individual records and readings from private surfers/recreational users of the Nigerian coasts.

Copernicus Marine Services wave height data are recorded as Global Ocean Wave Analysis and Forecast using hourly temporal extent since November 29, 2020 sourced from numerical models with level 4 processing and a high resolution of 0.083° × 0.083°

Surf – Forecast.com (2023) uses its Nigerian stations located at Lighthouse, Tarkwa Bay, and Shipwreck among its 7000 surf tracking spots worldwide complemented by satellite readings from partner sites such as Tide Forecast, Weather Forecast, Mountain Forecast, and Snow Forecast for metaocean data collections which includes ocean wave, tidal and wind parametrics.

SIGNIFICANT WAVE HEIGHTS (H) AND PERIODS (T) FOR SOUTH-WEST NIGERIA BIGHT OF BENIN COAST 2021 – 2022								
TIME	LAGOS H	KESUMETA H	OMOLOMO H	MEAN H	LAGOS T	KESUMETA T	OMOLOMO T	MEAN T
JAN	1.06	0.894999983	0.913749985	0.956249989	16.25	13.125	15.5	14.95833
FEB	1.06755	1.004583327	0.993333322	1.021822216	14.9585	15.20833333	15	15.05561
MAR	1.2225	1.20875	1.179166631	1.20347221	15.232	13.79166667	15.58333333	14.869
APR	1.302	1.291249988	1.291249975	1.294833321	16.857	16	13.625	15.494
MAY	1.3255	1.224999984	1.198749971	1.249749985	13.1875	16.375	14.625	14.72917

JUN	1.37	1.25666666 7	1.3449999 67	1.323888 878	13.429	16.333333 33	15.166666 67	14.976 33
JUL	1.663357 129	1.47499997 5	1.4462499 63	1.528202 355	14.643	15.25	15.875	15.256
AUG	1.758642 857	1.72874996 3	1.7287499 75	1.738714 265	14.44642 857	16.25	12.75	14.482 14
SEP	1.490642 857	1.40999998 3	1.4549999 5	1.451880 93	15.07157 143	14	12	13.690 52
OCT	1.345642 832	1.21999997 5	1.21375	1.259797 602	14.54464 286	16.875	15.875	15.764 88
NOV	1.155374 981	1.05749997 5	1.0512499 76	1.088041 644	15.75	15.25	14.75	15.25
DEC	0.947857 134	0.91499998 7	0.9316666 47	0.931507 923	15.07121 429	19.166666 67	15.5	16.579 29
MEA N	1.309088 983	1.22395831 7	1.2289930 3	1.254013 443	14.95340 476	15.635416 67	14.6875	15.092 11

Table 4.3: Wave data for selected stations in the Bight of Benin Nigerian Coast

TIME	Mean T	Mean H	Mean Wave Power Per Meter (kW/m)
JAN	14.95833	0.95625	507104.1
FEB	15.05561	1.021822	933686.8
MAR	14.869	1.203472	4913428
APR	15.494	1.294833	11877112
MAY	14.72917	1.24975	7454049
JUN	14.97633	1.323889	15002890
JUL	15.256	1.528202	1E+08
AUG	14.48214	1.738714	6.62E+08
SEP	13.69052	1.451881	44581808
OCT	15.76488	1.259798	8751754
NOV	15.25	1.088042	1740405
DEC	16.57929	0.931508	447519.2
MEAN	15.09211	1.254013	7943607

Table 4.4: Mean power regime in the Bight of Benin

Wave Regimes of Sea State		
Sea Storm Class	Wave Height(m)	Description
0	0	Calm Sea: Mirror- ed Steady, calm, and water surface

1	0 – 0.1	Rippled Sea: Very mild breeze, slightly rippled sea surface
2	0.1 – 0.5	Smooth Sea: wave initiation and formation
3	0.5 – 1.25	Gentle Breeze Sea: disturbed sea surface with large scattered wavelets
4	1.25 – 2.5	Moderate Sea: accelerated wave propagation and swelling to larger waves
5	2.5 – 4	Choppy Sea: rumbling and tumbling sea surface
6	4 – 6	Rough Sea: massive surface swells
7	6 – 9	High Sea: mild wave, gale with gusty wind
8	9 – 14	Very High Sea: strong wave gales and gust
9	14+	Phenomenal Sea: stormy high wave blocking visibility

Table 4.5: sea wave classification

The higher the renewable energy potential in a given geographical location, such as wave height, period, tidal range, thermal gradient and so on, the cheaper the cost of electricity and the more justified and easier the funding and harnessing of such resources will be. Hence, with fast pace in renewable energy investment and research, prices of modules and LCOE have dropped significantly in the last 10years, with further drops imminent in the next few years, though with wide variations across geographical locations.

Wave Height and wave period occurrence proportion in Nigerian offshore based on data Ojigi et al (2022), Koutitonsky et al (2011), Wavewatch 3, Wave Forecast.com, and various data collection sources are presented in Table 4.2 and Table 4.3.

Wave height (m)	% Occurrence
0.5 – 1.0	8.6
1 – 1.5	49.8
1.5 – 2.0	32.5
2.0 – 2.5	7.1
2.5 – 3.0	0.9
3.0 – 3.5	0.9

Table 4.6 Wave heights and occurrence rates

Wave Period (s)	% Occurrence
0 – 5	0
5 – 8	1.1
8 – 10	6.8
10 – 12	371
12 – 14	328

14 – 16	160
16 – 18	49
18 – 22	12

Table 4.7. Wave heights and occurrence rates

The wave and tidal energy data for this study as in table 3.4 are based on results of real – time, archive and forecast data from Copernicus Marine Services, Nigerian Navy Hydrography Office, NASA – Langley Earth Data, Tidal – Forecast.com, Surface – Forecast.com, offshore oil producing companies, and individual records and readings from private surfers/recreational users of the Nigerian coasts.

Copernicus Marine Services wave height data are recorded as Global Ocean Wave Analysis and Forecast using hourly temporal extent since November 29, 2020 sourced from numerical models with level 4 processing and a high resolution of 0.083° × 0.083° up to 2023.

Surf – Forecast.com (2023) uses its Nigerian stations located at Lighthouse, Tarkwa Bay, and Shipwreck among its 7000 surf tracking spots worldwide complemented by satellite readings from partner sites such as Tide Forecast, Weather Forecast, Mountain Forecast, and Snow Forecast for metaocean data collections which includes ocean wave, tidal and wind parametrics.

5.0. Discussion of Results

Based on results from near real-time SRA data estimates of some selected Nigerian coastal fronts obtained by Ojigi et al(2022) between 2009 and 2017, the average significant wave heights for three stations in Lagos are NNS Beecroft, 1.286m; Takwa Bay, 1.287m; and UWWS, 1.288m while FOB – E in and Forcados in Delta State are 1.29m and 1.256m respectively with Bayelsa's ABB recording 1.249m which similar to tidal heights general indicates marginal wave energy potentials with significant wave height ranging between 0.78m and 3.21m and periods 4.8s and 20.4s with near – shore waves being greatly influenced by bathymetric topography(Koutitonsky, et al, 2011) which is corroborated by the 2020 GMES and Africa Monthly Physical Oceanography Bulletin on East Atlantic which puts the significant wave height in the eastern Atlantic coast covering Nigeria, Benin, Togo and Ghana at 0.57m to 3.35m in August.

Generally, wave, tidal, and other ocean renewable energy resources are more expensive compared to fossil fired power plants and land based energy power generation plants due to being relatively new technologies and the challenging nature of marine environments which typically require higher levels of technical skills, material quality, regulatory conditions, environmental, security, and safety considerations among other things whose cost are however bound to reduce with time given more familiarity, advances in research and development, and wider adoption globally.

According to a 2015 report by the National Ocean Economics Program (NOEP) by the Middlebury Institute for International Studies at Monterey Center for the Blue Economy, the levelized cost of electricity for ocean renewable energy technologies is 0.12$/KWh – 0.2$/KWH with capital cost of $4.8/W to $5/W given average capacity factor between 35% and 55%, for offshore wind power; 0.32$/KWh – $0.65/KWh with capital cost of $4.8/W – $5.8/W given average capacity factor between 25% and 40%, for wave power; $0.2/KWh – $0.58/KWh with capital cost of $0.5/W – $1/W given capacity factor between 25% and 55% , for tidal power; and $0.08/KWh – $0.68/KWh with capital cost of $25/W - $37/W given average capacity factor between 92% and 98%, for Ocean Thermal Energy Conversion (OTEC) power system.

Wave Power and Tidal Power score below the proven technology threshold of 0.70 with a TEREVI of 0.66 and 0.65 respectively due primarily to the relatively low wave and tidal heights for the Southwest Nigerian coast of the Bight of Benin.

The average wave heights taken from 3 points in the Bight of Benin Nigerian coast with stations Lagos, Omolomo, and Kesumeta fall within sea wave class 2 to 4 and shows a mean significant wave height (SWH) of 1.25m and mean period of 15.1s with maximum SWH values recorded at rainy season between March and October peaking in August.

Wave Power and Tidal Power score below the proven technology threshold of 0.70 with a TEREVI of 0.66 and 0.65, respectively due primarily to the relatively low wave and tidal heights for the Southwest Nigerian coast of the Bight of Benin.

The average wave heights taken from 3 points in the Bight of Benin Nigerian coast with stations Lagos, Omolomo, and Kesumeta fall within sea wave class 2 to 4 and shows a mean significant wave height (SWH) of 1.25m and mean period of 15.1s with maximum SWH values recorded at rainy season between March and October peaking in August.

Various wave regimes determined by wave height differentials are classified as listed on Table 4.5 While Figures 5.1, 5.2, 5.3, 5.4, 5.5, and 5.6 shows the wave power potentials, wave periods, wave heights, and occurrences across the Bight of Benin Nigerian coast in the Gulf of Guinea. Wave energy cost of generation are relatively high due to technological infancy as a result of low learning rate making it commercially non – viable except for applications in pilot project for long-term studies and scientific development, given the relatively low significant wave heights. The HOMER optimization energy cost is $0.094003211/kWh, the Matlab energy generation cost simulation is $0.09t11/kWh, while the LCOE value is $0.082307404/kWh, and the TELCOE value is $0.092809/kWh.

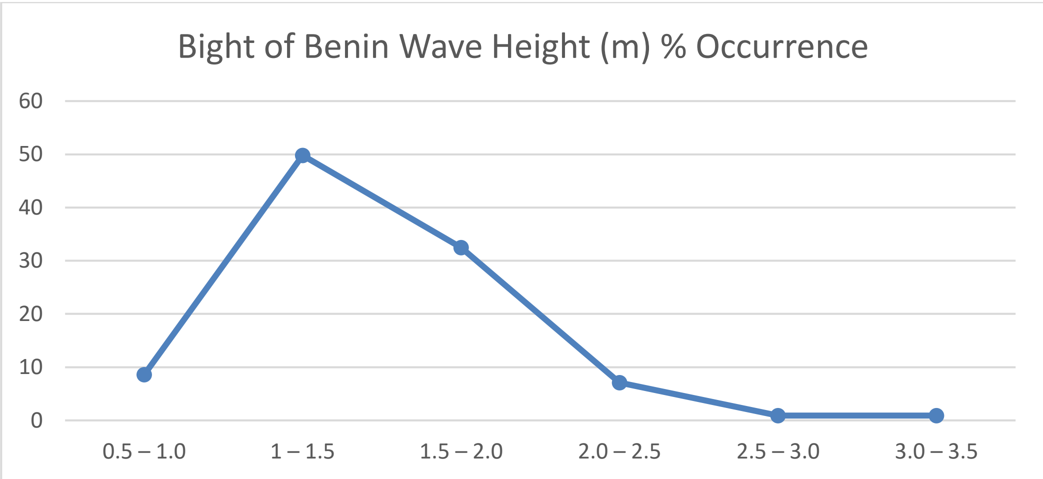

Fig. 5.2: Wave Height occurrence regime in the Bight of Benin

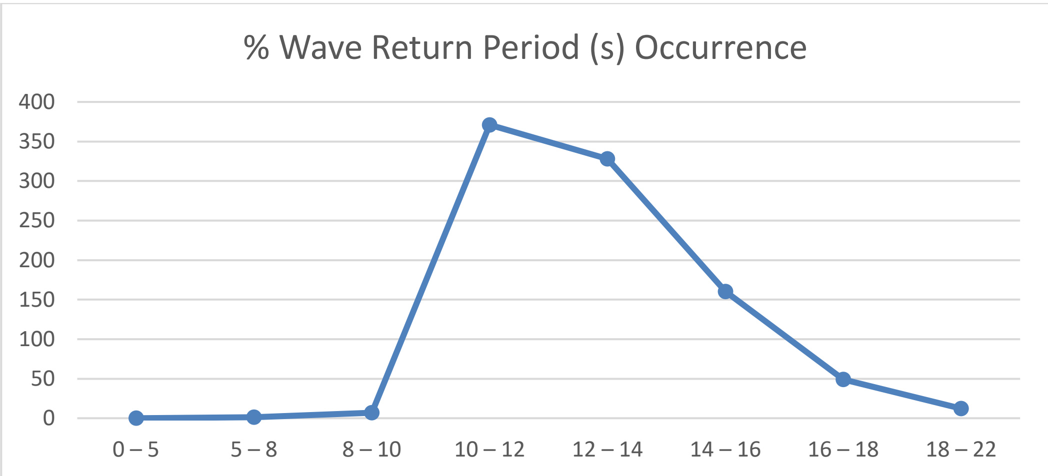

Fig. 5.3: Wave Return Period regime in the Bight of Benin

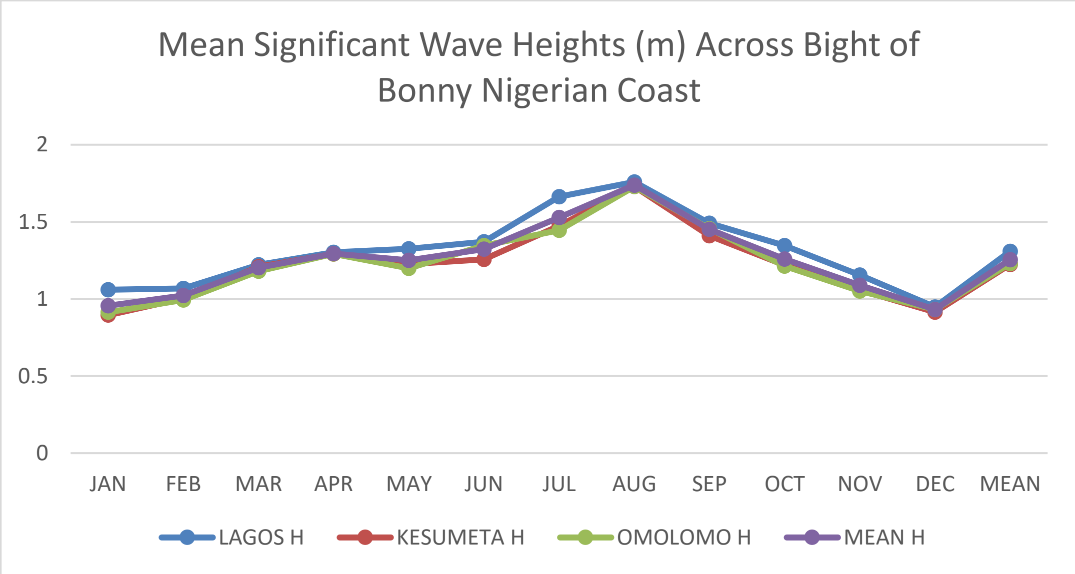

Fig. 5.4: Wave Height Variation in the Bight of Benin

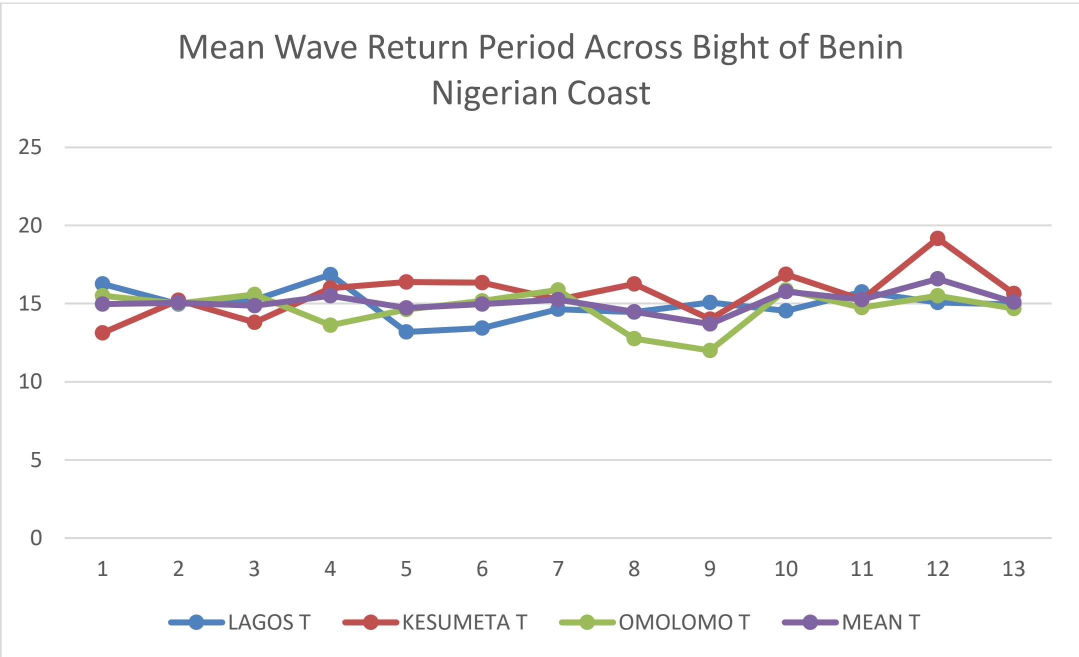

Fig. 5.5: Mean Wave Return Period of selected stations at the Bight of Benin

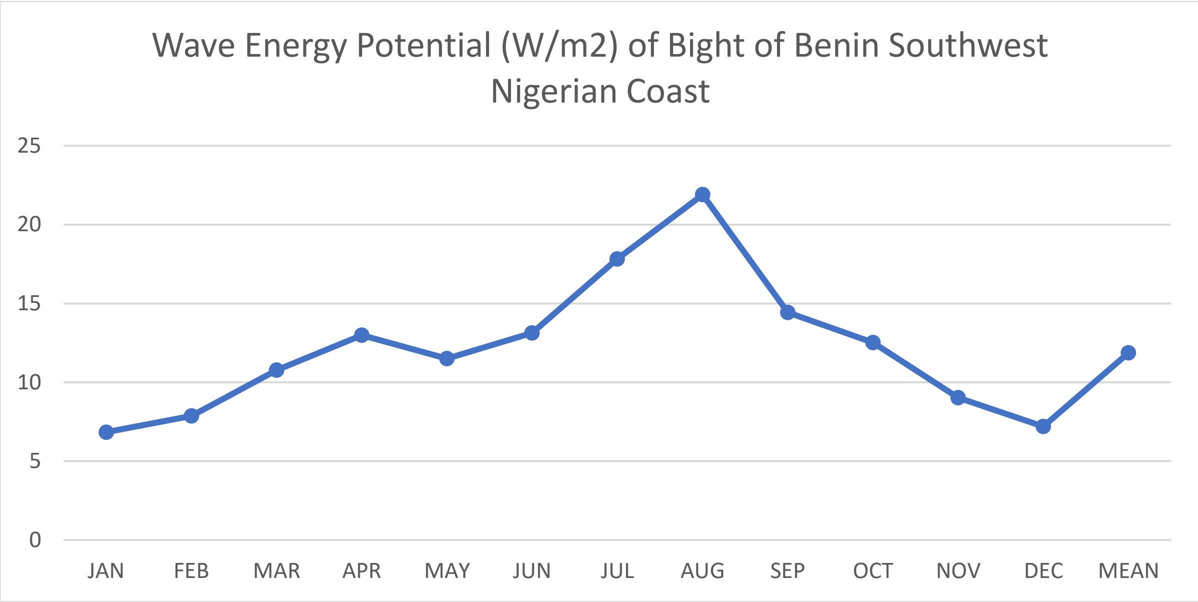

Fig. 5.6: Wave energy potentials in the Bight of Benin

6.0. Conclusion and Recommendation

Wave energy potential for the Bight of Benin along Southwest Nigerian coastline is generally between low to marginal with few periods of high potentials and above the highest average significant wave heights recorded in the results here presented.

The wave energy potential is higher towards the Bight of Bonny axis and also shows a pattern that tends to be highest at the extreme East at the interface of Bight of Bonny and West bordering the Republic of Benin waters.

By the foregoing and analysis of all indicators and viability measures, wave energy power generation in Southwest Nigeria is marginally commercially feasible for power generation with the best power conversion system carefully selected with respect to water depth, bathymetric topography, cost – effectiveness, and collaboration with the relevant oil and gas offshore operators concerning existing technologies, data, manpower, and infrastructure where applicable.

Thus, there is an urgent imperative for the establishment of ground several strategically sited ground data collection stations as part of the Renewable Energy Data Acquisition of Nigeria (REDAN) proposal and the harnessing of wave and other marine renewable energy resources with similar or higher promises beginning with pilot projects using best locations

7.0. Statements and Conflict of Interest Declarations

a. Conflict of Interest

The author has no relevant social, political, competing, or compromising affiliation to declare

b. Funding Statement

This research is fully self–funded by the author and therefore has no external sponsorship to declare

c. Financial Interest

The author has no immediate, short, medium, or long-term financial interest to declare with respect to this research

d. Employment

The authors of this research have no present, past, or future employment interest to declare with respect to this research

e. Social/Political Interest

The author of this paper has no past, present, or future political interest to declare with respect to this research

f. Authorship

I hereby declare that I, Christian Onuminya Okwori, is the only author of this research

g. Publication

This paper has never been published by another journal nor under consideration for publication elsewhere

h. Data Availability

The author is open to making available all relevant data from this study upon reasonable request

References

1. Egole, A.. Nigerian Unemployment Rate to Hit 41% in 2023 – KPMG. Punch Newspaper. April 11, 2023.
2. Rawat, A.; Ardhuin, F., Ballu, V.; Crawford, W.; Corela, C.; , and Aucan, J. Infragravity waves across the oceans. Geophysics Research Letters. Vol. 41. October 28, 2014. 41. DOI:10.1002/2014GL0616
3. Sheldon, B. and Alcocer, Y. Y. Shallow Water Waves. Study.com. February 18, 2022. https://study.com/academy/lesson/shallow-water-waves-definition-speed-calculation.html accessed November 8, 2023.
4. Clément, A.; McCullen, P.; Falcão, A.; Fiorentino, A. A.; Gardner, F.; Hammarlund, K.; Lemonis, G.; Lewis, T. ; Nielsen, K.; Petroncini, S.; Pontes, M. T. ; Schild, B. O.; Sjöström, P. ; Søresen, H. C.; Thorpe, T. Wave Energy in Europe: Current Status and Perspectives. Renewable and Sustainable Energy Review, 6 (5), Pp. 405-431. 2002.
5. Copernicus Marine Service. Global Ocean Waves Analysis and Forecast. Global Analysis of Wave Numerical Models. March 25, 2023. https://data.marine.copernicus.eu/product/GLOBAL_ANALYSISFORECAST_WAV_001_027/d
6. Dahunsi, A. M. and Foli, B. A. K. Assessment of Past and Future Potential of Ocean Wave Power in The Gulf Of Guinea. International Journal of Sustainable Engineering. Vol. 16(1), 18 October 2023.
7. Addeh, E. . NESI @10: Businesses Shutting Down over Escalating Cost of Energy, Says Dogara. Energy Central News. November 6, 2023.
8. FSF, 2003
9. Gemmill (1998) mathematical expression of wave theory
10. Google Map. Coastline of Southwest Nigerian States https://www.google.com.ng/maps/place/Ogun+State/@7.1146614,2.3301139,8z/data=!3m1!4b1!4m6!3m5!1s0x103b0deeeb1087cb:0xae67d82f51409ce8!8m2!3d6.9979747!4d3.4737378!16zL20vMDUxZHAw?entry=ttu accessed November 4th, 2023.
11. Gunn, K.; Stock-Williams, C. Quantifying the Global Wave Power Resource. Renewable Energy. Elsevier. 44: 296–304. doi: 10.1016/j.renene.2012.01.101. August, 2012.

12. Hasselmann, S., et al., The WAM model - A Third - Generation Ocean Wave Prediction Model. Journal of Physical Oceanography. Vol. 18, Pp 1775–1810. WAMDI Group. 1988.
13. Heimduo – Universal Source of Knowledge. What Does Fetch Mean in Waves? April 13, 2021. https://heimduo.org/what-does-fetch-mean-in-waves/#:~:text=Fetch%20is%20an%20important%20factor%20in Accessed February 12, 2023.
14. Herbich, J. B. (2000). Handbook of coastal engineering. McGraw-Hill Professional. A.117, Eq. (12). ISBN 978-0-07-134402-9. 2000
15. Holthuijsen, L. H. Waves in Oceanic and Coastal Waters. Cambridge: Cambridge University Press. ISBN 978-0-521-86028-4. 2007.
16. JUSTIA Patents. Ocean wave energy generator and parabolic concentrator system. January 23, 2019.
17. Kaiwen Zheng; Jian Sun; Changlong Guan; and Weizeng Shao. Analysis of the Global Swell and Wind Sea Energy Distribution Using WAVEWATCH III. Volume 2016, December 29, 2015. Article ID 8419580 | https://doi.org/10.1155/2016/8419580
18. Kayode, O.; Koya, O. A. Wave Energy Potential Along the Gulf of Guinea Coast of Nigeria. Applied Engineering Letters Journal of Engineering and Applied Sciences. March 2020.
19. Koutitonsky, V.; Smeti, H.; Atoui, A.; Queiroz, T.; Toulany, E.; Wango, E.; Adegbite, A. Akinnigbagbe, A. Nearshore Wave-Climate Modeling at Eroding Coastal Sites in Angola, Nigeria, Ivory- Coast and Tunisia. Technical Paper. NANO – Near Shore Hydrodynamic Group Report. October, 2013. DOI: 10.13140/2.1.1826.1289.
20. Kurniawan, A.; Chaplin, J. R.; Greaves, D. M.; Hann, M. Wave Energy Absorption by a Floating Air Bag. Journal of Fluid Mechanics. 812. DOI:10.1017/jfm. August, 2016.
21. Lainge, A. K. Guide to Wave Analysis and Forecasting: An Introduction to Ocean Wave. World Meteorological Organization. WMO – No 702, World Meteorological Organization ISBN 92-63-12702-6. Geneva 1998.
22. LGI – Lagos Geo Info. Geography of Lagos. 2018. http://www.lagosgeoinfo.com.ng/lagos.php#:~:text=Lagos%20has%20a%20coastline%20of%20180Km%20long%20and,elevation%20of%20less%20than%2015m%20above%20sea%20level. Accessed March 2, 2023
23. Magnusson, A. K; Reistad, M. Guide to Wave Analysis and Forecasting: Wave Generation and Decay. World Meteorological Organization. WMO – No 702, World Meteorological Organization ISBN 92-63-12702-6. Geneva 1998.
24. Mansir Nasir. Nigeria to Improve Electricity Access and Services to Citizens. World Bank. Press Release 2021/088/AFR. February 5, 2021.
25. MEPB – Ondo State Ministry of Economic Planning and Budget. https://www.mepbondostate.org/publication/ accessed March 3rd, 2023.
26. NOEP - National Ocean Economics Program. Offshore Renewable Energy Economic Costs. Center for the Blue Economy, Middlebury Institute for International Studies at Monterrey. May 20, 2015. https://oceaneconomics.org/offshore_renewables/costs/
27. Nwaokocha, C.; Waheed, A.; Layeni, A. *Estimation of Tidal Power Potential of Nigeria Coastal area*. Renewable Energy and Sustainable Development. ISBN: 978-1-63463-429-8. Nova Science Publishers Inc. 2015
28. Ojidi, M. L.; Dodo, J. D.; Opaluwa, Y. D.: Satellite Radar Altimetry-based Significant Wave Height Monitoring of some proposed Jetties in Nigeria Coastal Waters. National Association of Geodesy. National Journal of Geodesy (NJG). November, 2022. https://nag.com.ng/wp-content/uploads/2022/11/Satellite-Radar-Altimetry.pdf
29. Omono Okonkwo. Tinubu Says National Grid Serves 15% of Nigeria's Demand. Nairametrics. November 1, 2023.

30. Path Wave Energy project 2017
31. Planetcalc. The Waves and the Winds: Calculation of Wave Characteristics.2015. https://planetcalc.com/4406/ accessed February 12, 2023.
32. SETA – Sustainable Energy Fund for Africa. Assessing the Potential of Offshore Renewable Energy in Africa: A Background Paper. African Natural Resources Center (ANRC), African Development Bank (AfDB). December 2024.
33. Ssentongo, G. W.; Ukpe, E. T.; Ajayi, T. O. *Marine Fishery Resources of Nigeria: A Review of Exploited Fish Stocks*. Programme for the Development of Fisheries In the Eastern Central Atlantic Fishery Committee for The Eastern Central Atlantic. Publications Division, Food and Agriculture Organization of the United Nations, Via delle Terme di Caracalla, 00100 Rome, 1986. CECAF/ECAF SERIES 86/40 (En).
34. Surf – Forecast.com. Surf Forecasts and Surf Reports Worldwide. Snow – Forecast.com, February, 2023.
35. Taro Kakinuma. Long-Wave Generation due to Atmospheric-Pressure Variation and Harbor Oscillation in Harbors of Various Shapes and Countermeasures against Meteotsunamis. Natural Hazards. May 2019. DOI:10.5772/intechopen.85483.
36. Titah-Benbouzid, H.; Benbouzid, M. An Up - to - Date Technologies Review and Evaluation of Wave Energy Converters. International Review of Electrical Engineering-IREE, Vol. 10 (1): Pp. 52-61. 2015.
37. Tobi Awodipe. As Rising Energy Cost, FX Crisis De-industrialise Nigeria. The Guardian Newspaper. November 4, 2023.
38. Toffoli, A.; Bitner-Gregersen, E. M. Types of Ocean Surface Waves: Wave Classification. Basic Hydrodynamics and Wave Dynamics. March 6, 2017.
39. Tribune. Ondo Multipurpose Deep Seaport: Residents Express Readiness for Improved Economy. Nigerian Tribune. September 15th, 2020.
40. Tulashie, S.K. Odai, R.; Dahunsi, A. M.; Atisey, S.; and Amenakpor, J. Feasibility Study of Wave Power in Ghana. International Journal of Sustainable Engineering. Vol. 15 (1), pg299-311, 15 November 2022.
41. Ukwuaba, S. I. *Tidal Power Potentials in Nigeria: Investigative Study Of Port Harcourt Estuaries*. Department of Mechanical Engineering, Federal University of Petroleum Resources, Effurun, Delta State 2013. https://lekanbakarefoundation.org/News/the-emergence-of-wave-and-tidal-energy-as-an-alternative-source-of-energy-in-nigeria/#:~:text=In%202013%2C%20Engineer%20S.I.%20Ukwuaba%2C%20Head%2C%20Department%20of,along%20the%20coastline%2C%20has%20already%20been%20carried%20out. Accessed September 24, 2023.
42. Wang et al. The Wave Focusing Effect of a Parabolic Wall. ASME 2004 23rd International Conference on Offshore Mechanics and Arctic Engineering, American Society of Mechanical Engineers, 2004.
43. Wave Energy Potential Website. Wave Energy Potential in Nigeria. Wave Energy. June 6, 2021. https://waves-energy.co/2021/06/06/wave-energy-potential-in-nigeria/#:~:text=The%20total%20coastlines%20of%20Nigeria%20%3A%20853%20km,23%25%20The%20average%20wave%20energy%20%3A%207.5%20KW%2Fm accessed February 4, 2023.
44. Wave Energy. *Wave Energy Potentials in Benin*. Wave Energy. January 12, 2022. https://waves-energy.co/2022/02/12/wave-energy-potential-in-benin/
45. Xizhuo Zhang; Longfei Zhang; Yujun Yuan; Qiang Zhai. Life Cycle Assessment on Wave and Tidal Energy Systems: A Review of Current Methodological Practice. International Journal of Environmental Research and Public Health. Vol 17 (5), Pp 604, March 2, 2020. Int J Environ Res Public Health. DOI: 10.3390/ijerph17051604.