Prospects of ocean-based renewable energy for West Africa's sustainable energy future

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Abstract

Purpose – The limited supply of fossil fuels, constant rise in the demand of energy and the importance of reducing greenhouse emissions have brought the adoption of renewable energy sources for generation of electrical power. One of these sources that has the potential to supply the world's energy needs is the ocean. Currently, ocean in West African region is mostly utilized for the extraction of oil and gas from the continental shelf. However, this resource is depleting, and the adaptation of ocean energy could be of major importance. The purpose of this paper is to discuss the possibilities of ocean-based renewable energy (OBRE) and analyze the economic impact of adapting an ocean energy using a thermal gradient (OTEC) approach for energy generation.

Design/methodology/approach – The analysis is conducted from the perspective of cost, energy security and environmental protection.

Findings – This study shows that adapting ocean energy in the West Africa region can significantly produce the energy needed to match the rising energy demands for sustainable development of Nigeria. Although the transition toward using OBRE will incur high capital cost at the initial stage, eventually, it will lead to a cost-effective generation, transmission, environmental improvement and stable energy supply to match demand when compared with the conventional mode of generation in West Africa.

Practical implications – This study will be helpful in determining the feasibility, performance, issues and environmental effects related to the generation and transmission of OBRE in the West Africa region.

Originality/value – The study will contribute toward analysis of the opportunities for adopting renewable energy sources and increasing energy sustainability for the West Africa coast regions.

Keywords Ocean energy, Sustainability, Thermal energy, Renewable energy

Paper type Research paper

1. Introduction

The negative environmental footprints from fossil fuel energy generation and the prospect of inevitable exhaustion of the fuel reserves encourage many countries and regions to explore and integrate renewable energy resources (RER), a process supported by the International Energy Agency (IEA) as well as the Intergovernmental Panel on Climate Change (IPCC). The estimated potential of an ocean as a renewable energy source is only next to solar energy, and hence, it can readily replace the existing fossil-based energy sources (Narula, 2019). The latter is especially relevant for sub-Saharan African countries, which suffer from environmental

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degradation and poorly equipped environmental protection, which threaten economic security and well-being of the population [2,3].

Nigeria, likewise, strongly depends on fossil fuel, especially oil and gas, to meet its energy demands. Despite the huge oil and gas reserves in Nigeria, inadequate energy supply remains a noticeable barrier to the economic growth of the country and a region. A Nigerian coastal area in the south-south region of Nigeria has a daily average demand of 100 MW (Aseigbu, 2014). However, at present, the installed capacity is 10.396 GW and available capacity 6.056 GW, which exposes deficiency in energy delivery. As a result of its abundance of RER combined with high demand for energy, renewable energy development in West Africa is attracting increased attention from financiers and decision makers (Merem *et al.*, 2017).

The development of renewable energy sources and improvement of efficiency of energy transfer and usage of conventional energy sources are most promising solutions for a sustainable energy future. Ocean energy is a sustainable energy source that has a high potential for providing a vast amount of the world energy demands. It holds a huge amount of power and it covers over 70 percent of the planet Earth's surface (Secretariat of the Pacifi, 2009). The ocean surface behaves like a solar collector and has the ability to capture the heat energy form the sun (Khan *et al.*, 2017). Ocean energy has several advantages when compared with other sustainable sources such as biomass, solar, wind, etc. It is abundant in nature, readily available, provides a lower environmental impact than other renewable sources and it is predictable. These advantages give it a potential for electricity production (Melikoglu, 2018a). Ocean energy could provide energy independence, power desalination plants, as well as create jobs. The improvement in ocean energy designs helps to provide dependable and clean sustainable power to make available the resources needed to match the increasing energy demands (Melikoglu, 2018a).

However, while being one of the most promising renewable energy sources, ocean energy is still underdeveloped as compared to other renewables (Astariza and Iglesias, 2015). According to the IEA, there are five different technologies of harnessing the ocean energy: tidal power, tidal or marine current, wave power, temperature gradient and salinity gradient. While tidal and wave energy conversion has picked up remarkable attention (International Energy Agen, 2017), other conversion techniques, which are also developed, include the production of drinking water via desalination, hydrogen production by electrolysis and supplying compressed air for aquaculture.

There has been significant progress in the production of electricity through ocean energy in the world. The ocean tidal, osmotic, wave and thermal resources have potentials of 800, 2,000, 8,000–80,000 and 10,000–87,600 TWh annually, which is more than the global 16,000 TWh per year (Khan *et al.*, 2017). According to the World Energy Council (WEC), 0.5 GW of commercial ocean energy generation capacity is in operation and about 1.7 GW is under construction (World Energy Council, 2016). About 99 percent of this generation is attributed to tidal power. About 11 MW is attributed to tidal current, 2 MW of wave power and no ocean thermal energy conversion (OTEC). WEC also stated that about 15 GW of ocean energy projects are at various stages of development, with majority being generated by tidal power (11.5 GW), followed by tidal current (2.6 GW), wave (0.8 GW) and OTEC (0.4 GW) (WEC). In Africa, there has been little progress in the production of electricity through ocean energy. Some countries such as Ghana and South Africa have initiated projects to harness energy through the ocean. A wave energy array with a 400 KW of capacity containing six devices has been installed and is operational in Ghana (Offshore Wind Biz and South, 2015).

Generating electricity with ocean energy has been a long topic of research (AbuBakr, 2011). The studies considered harnessing the ocean energy in China (Wang *et al.*, 2011), in Caspian Sea (Alamian *et al.*, 2014), Spain (Nalon River) (Eduardo *et al.*, 2016), the UK

(Angeloudis *et al.*, 2017), Southern Alaska (USA) (Ye and Lindsay, 2014), Thailand (Kompor *et al.*, 2018), Taiwan (Chen *et al.*, 2018a), Australia (Hemer *et al.*, 2018) and Indonesia (Alifdini *et al.*, 2018). The proposed technologies for harnessing ocean energy include thermal energy conversion (Aydin *et al.*, 2014), floating point absorbers (Alamian *et al.*, 2014), micro-turbine arrays (Eduardo *et al.*, 2016), mechanical wave front (Collins and Abayomi, 2013) and wave energy converters (Liliana and Florin, 2017; Nabavi *et al.*, 2018). The economical analysis of the practicality of using tidal energy has been presented in (Eva *et al.*, 2017), while the need for predicting available ocean's energy for any future electricity generation scenario is advocated in (Angeloudis *et al.*, 2017). In Nigeria, Ukwuaba (2013) calculated that the possible power that could be generated is 6.9 MW and the best possible location with the highest tidal reading was at bight of Bonny along Port Harcourt coastline. Collins and Abayomi (2013) investigated the utilization of mechanical wave as a means of harnessing the waves generated in the coastal belts of Nigeria. Amoo (2018) evaluated the resource potential of tidal energy at Apapa Lagos, Lagos Bar and Bakana New Calabar River in Nigeria. Okoli *et al.* (2017) developed a simulation model for tidal energy extraction in Qua Iboe River in Nigeria using tidal current turbine, while Nwaokocha *et al.* (2015) evaluated the tidal power potential of Nigeria coastal area.

The efficiency of OTEC systems depends upon environmental parameters and their variability. Neural networks have been used to predict, for example, ocean coastal currents (Ren *et al.*, 2018) and sea surface temperature (Ouala *et al.*, 2018). Such results could be useable to improve the accuracy of OTEC modeling as well.

Summarizing, ocean-based renewable energy (OBRE) has gained a decent ground in the world. Many countries have proposed models to harness ocean power. West African countries, such as Nigeria or Ghana, are also actively looking to harness this energy because of their proximity to the Atlantic Ocean. However, few works have concentrated on the economic and financial achievability of implementing an OBRE because it relates to the West African region as well as ways to further increase the efficiency of OBRE. Regardless of the advantages of ocean energy, few studies have concentrated on the economic impact and attainability.

This paper discusses the prospect and the economic impact of OBRE as it can be applied in West African countries, using Nigeria as a case study. We propose the OBRE design and analyze the economic impact indicators.

2. Methodology

2.1 Geography and analysis of alternatives

The West African region is endowed with multiple mineral resources such as gold, crude oil, iron ore, etc. Nigeria has produced crude oil since the 1960s, with Liberia, Ghana, Sierra Leone Cote d'Ivoire and recently also emerging as oil producers (Jalloh, 2011). Oil derivatives such as gasoline and diesel can be used to power electric generators. The research on natural ocean energy resources in Africa in general and in West Africa, specifically, is scarce and lacks of data, as was indicated in recent review of current status and future of ocean energy resources (Melikoglu, 2018b).

Nigeria has about 834 km of coastline that runs through seven states: Ogun, Ondo, Akwa-Ibom, Bayelsa, Cross-rivers, Lagos and Rivers bordering the Atlantic Ocean. Bight of Bonny, Bight of Benin, Cross River Estuaries and Lagos lagoon are water bodies that hold the potential to operate an OBRE. Table I shows the wave characteristics of these locations. Significant ocean wave height values near West Africa coast (reference point 6°28′N 11°56′E) is in the range of 1.38–3 m, with a maximum variation of only 24 percent (Liliana and Florin, 2017). Liliana and Florin (2017) recommend using attenuator and terminator-type devices for harnessing ocean energy near the West Africa coast.

The coastal regions of Nigeria have a high temperature gradient as compared with the energy generation potential of tidal waves. The temperature gradient, as energy potential for a Nigerian coastal region at latitude $4^{\circ}00'$–$4^{\circ}16'$N, and longitude $7^{\circ}16'$–$7^{\circ}19'$E, has been evaluated to be at 22 and 24 K across 1 km from the sea water surface during rainy and dry seasons, respectively (Met Ocean View and "Hindcast"). The ocean temperature is highest at the surface of the ocean of about 0–200 m with about 26–30 °C and from the depth of about 1800 m below the sea level, the temperature goes as low as 2–4 °C. The temperature difference is relatively constant throughout the year (Figure 1).

Nigeria has one of the highest potentials for OTEC among other renewable energy sources (RES) (Oko and Obeneme, 2017). Considering low energy potential of ocean's waves near the Nigerian coast, here we propose using a thermal gradient approach (OTEC) (Magesh, 2010) for energy generation.

2.2 Ocean thermal energy conversion (OTEC)

OTEC is a technique of producing power by utilizing the normal temperature difference between shallow and deep waters. The distinction in the temperature between the warm and cold water is used to drive a turbine. The temperature difference that is required to be able to produce optimal power is ideal to be at least 20°. It is estimated that the power that could be generated with this temperature distinction is $2 \cdot 10^{12}$ W (Wang *et al.*, 2011). This difference in temperature is usually constant all year round.

Further, we describe the principles of OTEC in more detail. A liquid with low boiling point, for example, ammonia, is transformed into vapor by warming it up with the warm surface water. This vapor at this point turns a turbine to produce power. The vapor is condensed by utilizing the cold ocean water. The pressure, weight, temperature and volume of a liquid are the different characteristics that OTEC relies upon. This is supported by the ideal gas law as described in eqn 1 below:

$$PV = nRT, \tag{1}$$

Here, P – Gas pressure; V – Volume; n – Gas amount in moles; R – Ideal gas constant; T– Absolute temperature.

Different OTEC designs have been proposed; these includes the open cycle, closed cycle, hybrid OTEC systems and advanced OTEC systems (Finney, 2008). In the open OTEC cycle, a generator is driven by steam when a warm ocean water is changed over to steam used in driving the generator. The warm ocean water acts as a working fluid. Desalinated water can be obtained when the cold sea water cools the steam or the resulting liquid can be released into the ocean (Nihous and Syed, 1997). In the closed OTEC cycle, ammonia is used as a working fluid because of its low boiling point. The ammonia is converted into vapor by the warm sea water to turn a turbine that is connected to a generator. The cold sea water converts the ammonia vapor into liquid, and then, the ammonia liquid is converted into high-pressure ammonia and the cycle continues in a closed loop (Etemadi *et al.*, 2011; Faizal and Ahmed, 2013). In the hybrid OTEC cycle, the system combines the properties of the open and closed systems. This further increases the efficiency of the OTEC system [433]. Also different

Table I.
Wave characteristics of different ocean bodies in Nigeria (according to Met Ocean View (Met Ocean View))

Location	Highest mean wind speed (knots)	Highest mean wave height (m)
Bight of Bonny	7.5	1.24
Bight of Benin	7.6	1.4
Cross River Estuaries	5.6	0.9

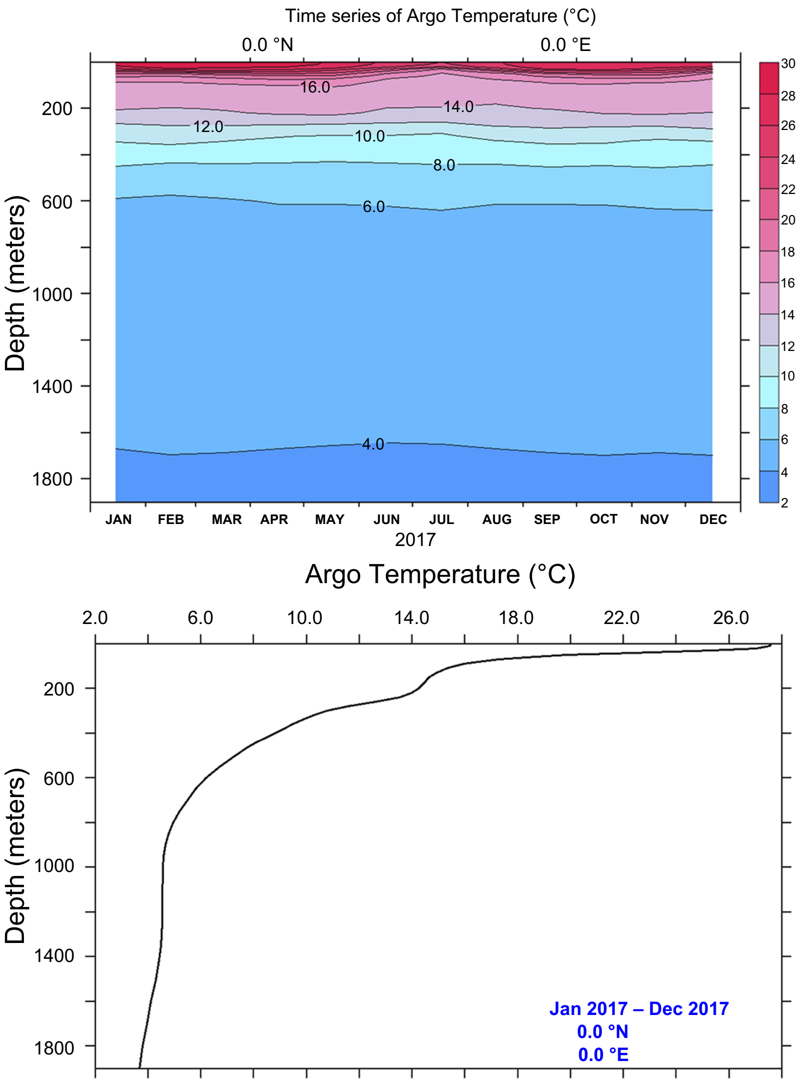

Figure 1.
Graphical representation of the change in temperature with ocean depth

advanced OTEC cycles such as the Kalina (Uehara and Ikegami, 1993), Uehara (Uehara *et al.*, 1994) and double-stage Rankine (Ikegami *et al.*, 2018) cycles have been further developed to increase the efficiency of the OTEC systems.

2.3 Prospects of OTEC in Nigeria

There are temperature variations with the depth of Atlantic Ocean water. About 5–50 m depth, it is relatively warm. This temperature drops rapidly to about at 1,000 m and an average of 3.2 °C is maintained at sea bed. This made the average temperature difference about 26 °C. This difference in temperature has made the coastal regions in Nigeria a viable location for the installation of an OTEC plant.

Figure 2 shows the proposed model for the OTEC plant in Nigeria used for this study. This model employed the use of a temperature sensor and an automatic heater, which can automatically alter the temperature of the evaporator to obtain a constant temperature over the year and further improve efficiency. The proposed plant consists of the following stages:

(1) a closed Rankine cycle (1–4);

(2) heated ocean water which is taken back or returned to the ocean (5–8);

(3) cold ocean sea water that is taken from the profundity or intermediate depth of the sea (11–14);

(4) a stream of desalinated fresh water (15–16);

(5) a control center that consist of a temperature sensor and automatic heater to alter the evaporator temperature (15–17); and

(6) the connection to the generator and the grid to provide sufficient electricity (9–10).

2.4 Plant model

In order to estimate the parameters for the design for a 100 MW OTEC plant, the following assumptions are made:

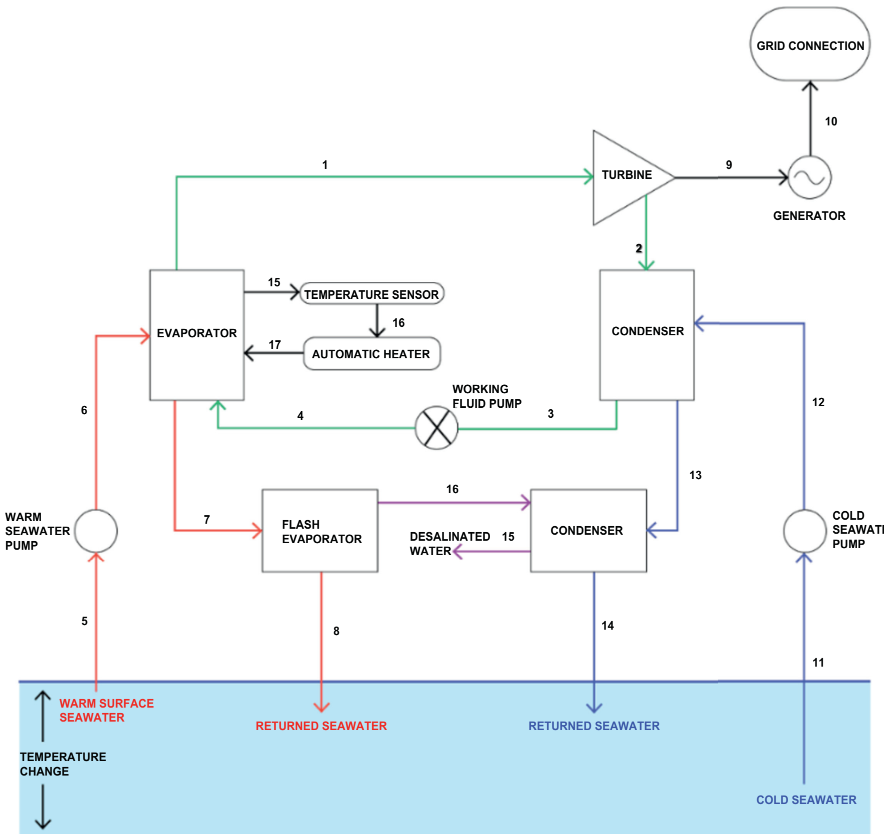

Figure. 2.
Proposed OTEC system model

(1) A 20 m diameter pipe that extends to a depth of about 10 m to allow the flow of 26 °C water at 500 m^3/s.

(2) A 15 m diameter pipe that extends to a depth of about of 1,200 m to allow the flow of 4 °C water at 300 m^3/s.

(3) A 30 m diameter pipe used to return condensed steam to the ocean.

The thermodynamic process of the OTEC plant is modeled as the saturated Rankine cycle. The analysis is based on the thermodynamic diagram, as shown in Figure 3. The heat added in the cycle, Process 4–1, is given as:

$$H_a = h_1 - h_4, \tag{2}$$

Here, $H_a(kJ/kg)$ – Heat added in the cycle; $h_k(kJ/kg)$ – Working fluid enthalpy.

Turbine work T_w, Process 1–2 is given as:

$$T_w = h_1 - h_2, \tag{3}$$

The heat rejected $H_r(kJ/kg)$, Process 2–3 is:

$$H_r = h_2 - h_3, \tag{4}$$

The pump work $W_p(kJ/kg)$, Process 3–4 is given as:

$$W_p = h_4 - h_3 \approx V_3(P_4 - P_3) = V_{KF}(P_E - P_K) = V_{KF}\Delta P, \tag{5}$$

Here, $V(m^3/kg)$ is the specific volume; $P(kP_a)$ is the absolute pressure of the working fluid; P_E is the evaporated pressure; P_K is the condensed pressure; V_{KF} is the condensed pressure P_K at liquid saturation line (*f*).

The net work $W_{\text{net}}(kJ/kg)$, is obtained by:

$$W_{\text{net}} = W_t + W_p = h_1 - h_2 - (h_4 - h_3) = h_1 - h_2 - h_4 + h_3, \tag{6}$$

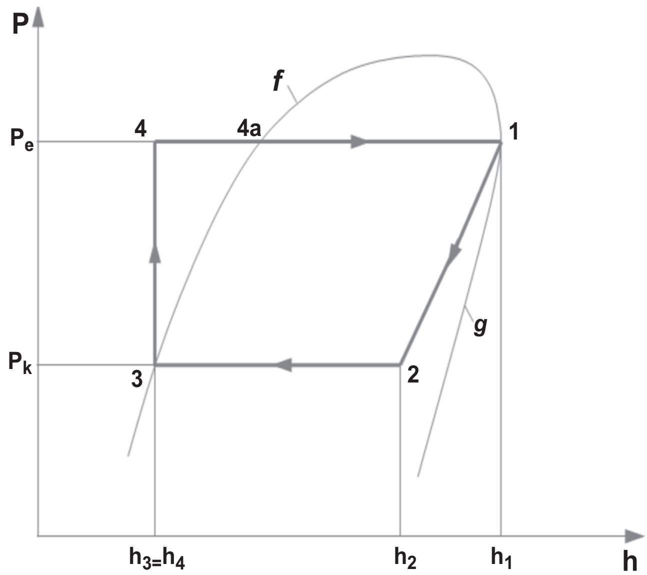

Figure 3.
Thermodynamic Rankine cycle

The Rankine efficiency, η_{TH} can be obtained by:

$$\eta_{TH} = \frac{w_{\text{net}}}{q_a} = \frac{W_{\text{net}}}{Q_a} = 1 - \frac{h_2 - h_3}{h_1 - h_4}, \tag{7}$$

Here, w_{net} is the net addition rate of the plant; q_a is the net power output of the plant.

The power output of the Rankine power plant $w_{\text{net}}(kW)$ is given as:

$$w_{\text{net}}(kW) = mw_{\text{net}}(kW) = m(h_1 - h_2 - h_4 + h_3), \tag{8}$$

Here, $m(kg/s)$ is the flow rate of working fluid.

The net power P_{net} produced from entire plant after considering the pumping requirement becomes:

$$PW_{\text{net}} = PW_{tg} - PW_{\text{wsw}} - PW_{\text{csw}} - PW_{wf}, \tag{9}$$

Here, PW_{tg} is the power of the turbine generator; PW_{wsw} is the pumping power of the warm sea water; PW_{csw} is the pumping power of cold sea water; PW_{wf} is the pumping power of working fluid.

The turbine generator PW_{tg} is given by:

$$PW_{tg} = m_{wf}\eta_t\eta_g(h_1 - h_2), \tag{10}$$

Here, m_{wf} is the working fluid flow rate; η_t is the turbine efficiency; η_g is the generator efficiency.

The turbine efficiency is given as:

$$\eta_t = \eta_m\eta_e, \tag{11}$$

Here, η_t is the theoretical efficiency; η_m is the mechanical efficiency; η_e is the electrical efficiency and is defined as:

$$\eta_e = \frac{H_{ad} - (\Delta h_N + \Delta h_R + \Delta h_{\text{Ex}} + \Delta h_D + \Delta h_{\text{WET}})}{H_{\text{ad}}}, \tag{12}$$

Here, H_{ad} is the adiabatic heat drop; Δh_N is the kinetic energy loss in nozzle; Δh_R is the rotor loss; Δh_{Ex} is the exhaust loss; Δh_D is the rotary disc loss due to friction and windage; Δh_{WET} is the losses due to wetness of steam.

The pumping power of the cold sea water PW_{CSW} is given by the equation below:

$$PW_{\text{CSW}} = \frac{\Delta P_{\text{csw}}\, m_{\text{csw}}\, v_{\text{csw}}}{\eta_{\text{csp}}}, \tag{13}$$

Here, m_{csw} is the flow rate of cold sea water; v_{csw} is the specific volume of the cold sea water; ΔP_{csw} is the pressure difference of cold sea water piping; η_{csp} is the efficiency of cold sea water pump.

The pumping power of warm sea water PW_{WSW} is given by:

$$PW_{\text{WSW}} = \frac{\Delta P_{\text{WSW}}\, m_{\text{WSW}}\, v_{\text{WSW}}}{\eta_{\text{wsp}}}, \tag{14}$$

Here, m_{wsw} is the flow rate of warm sea water; v_{wsw} is the specific volume of the warm sea water; ΔP_{wsw} is the pressure difference of warm sea water piping; η_{wsp} is the efficiency of warm sea water pump.

The working fluid pumping power PW_{WF} is given by:

$$PW_{WF} = \frac{\Delta P_{wf}\, m_{wf}\, v_{wf}}{\eta_{wf}}, \tag{15}$$

Here, m_{wf} is the flow rate of working fluid; v_{wf} is the specific volume of the working fluid; ΔP_{wf} is the pressure difference of working fluid; η_{wf} is the efficiency of working fluid pump.

2.5 Economic impact of ocean-based renewable energy

An analysis is conducted from the perspective of cost, energy security and environmental protection. This analysis will be helpful in determining the feasibility, performance, issues and environmental effects related to the generation and transmission of OBRE in the West Africa region. As the OBRE is being considered in this paper, other sources of energy generation will be considered as a baseline in this comparison, using fossil fuels because it is most dominant in West Africa.

2.5.1 Cost. The cost of developing an OTEC system in the West African region can be divided into the recurring and non-recurring costs. The costs that frequently occur mostly on a yearly basis such as operations and maintenance cost, repair, replacement, miscellaneous cost, among others, are known as recurring costs. Recurring costs are summed up as the operations and maintenance cost (O and M). The non-recurring costs include the initial cost of the plant, cost of deployment and installation, cost of commissioning amongst others and is summed up as the installed capital cost (ICC). Therefore, the total lifecycle cost of an OTEC plant can be given as:

$$\mathrm{LCC} = \sum_{I=1}^{2} C_i, i = \mathrm{ICC}, \mathrm{O\,and\,M}, \tag{16}$$

Here, C_i is the present value of each cost component, ICC and O and M are the cost components for the installed capital cost and operations and maintenance cost of the OTEC plants.

The relation that shows the OTEC ICC varies with the plant capacity as:

$$\mathrm{ICC} = 53,000 P_{\mathrm{net}}^{-0,42}, \tag{17}$$

The O and M costs of the OTEC plants are relatively low. They are about 1.4 percent–2.7 percent of the total investment cost. The O and M are assumed constant yearly, and they are given below:

$$C_j = C_{j/y}\left(\frac{1+i}{1+d}\right) \frac{1-\left(\frac{1+d}{1+i}\right)^N}{1-\left(\frac{1+d}{1+i}\right)}; j = \mathrm{O\,and\,M}, \tag{18}$$

Here, $C_{j/y}$ is the yearly O and M cost, i and d are the interest rate and the inflation and escalation rate, respectively, and N is the life span of the system.

2.5.2 Energy security and environmental protection. OBRE is generally available throughout the year, and it provides a reliable and secure way to generate electricity, especially in coastal areas. It is a source of clean, sustainable energy that harnesses the ocean water that is abundant and almost unlimited to generate electricity. OTEC does not depend on climate conditions and does not discharge any CO_2.

Despite the many positives of OTEC, it has some disadvantages. The environmental concerns include the leakage of the working fluid such as ammonia or isobutene if the pipe is damaged. These leakages could potentially cause harm to sea creatures as well as humans and pollute the surrounding ocean body. Other risks, associated with OTEC, include the electrical hazards, rotating machinery, shop and maintenance hazards, etc., which could result in the injury of the operating personnel.

3. Results and discussion

3.1 Energy characteristics of the OTEC power plant

We used a personal computer with AMD (A6-5200 APU) Quad CPU, 4.00 GB RAM with 750 GB hard drive running on Microsoft Windows 8 Professional 64 bit. All calculations were performed using MATLAB (version R2015b).

The design and input parameters for the proposed 100 MW OTEC plant are presented in Table II.

For the analysis, to be able to obtain a 100 MW OTEC power plant, ammonia should be used as a working fluid because of its low boiling point characteristic of about $-33.34\,^{\circ}$C. It has a density of 597.908kg/m^3 and a specific heat capacity of 4.872kJ/kgK. As an alternative, isobutane also can be used as a working fluid, which has a boiling point of about $-11.7\,^{\circ}$C; however, it was not considered in this study.

OTEC utilizes the change in temperature ΔT between the hot water surface ($\sim 24-30^{\circ}C$) available at about 0–200 m and the cold water in the deep ocean (available at about 800–1,000 m. The temperature difference that is required to generate about 100 MW of electrical power from the OTEC is required to be about 20 $^{\circ}$C. The change in temperature that exists at the coastline of Nigeria is about 26 $^{\circ}$C, and this is very suitable in utilizing OTEC. The proposed plant can supply the warm sea water at 200 and 395 m^3/s and also supply cold sea water at 160 and 280 m^3/s to the evaporator and condenser during dry and rainy seasons, respectively, with ammonia flow rate of 4 m^3/s to produce a gross power of 100 MW all year round. This flow rates is achieved by the proposed 11 and 16 m diameter of the cold and warm seawater pipe. The turbine efficiency was found to be 80 percent, generator efficiency as 95 percent and the pumps efficiency as 90 percent.

3.2 Economic impact characteristics of the OTEC power plant

The economic characteristics of OTEC plant are as shown in Table III. The ICC was calculated to be 8,500 US$/kW, and the annual O and M costs, which is 2 percent of the ICC, is calculated to be 170 US$/kW/year for the 100 MW OTEC plant. The unit cost of energy is

Parameters	Values	Unit
Working fluid	Ammonia	
Ammonia density	597.908	kg/m^3
Ammonia specific heat capacity	4.872	kJ/kgK
Turbine efficiency	0.80	
Turbine rated power	100	MW
Generator efficiency	0.95	
Pumps efficiency	0.90	
Warm seawater inlet temperature	25 and 30	ºC
Cold seawater inlet temperature	3 and 4	ºC
Pipe length of warm seawater	10	m
Pipe diameter of warm seawater	20	m
Pipe length of cold seawater	1,200	m
Pipe diameter of cold seawater	15	m
Heat exchangers conductivity	14	W/m K
Surface sea water temperature	29	ºC
Deep cold water temperature	3	ºC
Water density	1025	kg/m^3
Water specific heat capacity	4.182	kJ/kgK
Evaporator pressure	9.78	Bar
Condenser pressure	6	Bar
Friction loss factor	0.02	

Table II.
Design and input parameters for the 100 MW OTEC plant

0.15 US$/kWh, which falls between the range of an estimated 0.03 and 0.18 US$/kWh for a 100 MW power plant, as proposed in Kempener and Neumann (2014).

3.3 Comparison between electricity generation using fossil fuel and ocean energy

Table IV shows the comparison between the use of natural gas and ocean thermal energy for electricity generation in Nigeria. Natural gas is presently the main energy source that is used for electricity generation in Nigeria. However, the use of ocean thermal energy provides an efficient way of generating power as compared with natural gas.

3.4 Existing skills and infrastructure

Nigeria's offshore-engineering skills and support infrastructure, currently concentrated in the oil and gas industry, can be beneficial for developing the offshore OTEC plants while exploiting the already established marine industrial base. Recently, Nigeria's oil and gas industry has suffered a period of decline, which provides good opportunities to transferring the required technical skills and resources toward Nigeria's developing the OBRE sector, thus accelerating the delivery of RER. Moreover, the OTEC plants provide an opportunity for economic development of Nigerian coastal regional communities through increased port activities and supply chain industries.

3.5 Environmental impart

Apart from advantages, the OTEC plant will have some inevitable disadvantages for environment. The required infrastructure (power lines, power substations) will have negative visual effect on the seashore and may reduce the touristic attractability of natural scenery. Sea construction will inevitably lead to sediment displacement, which will affect negatively local marine habitat. The power lines will produce electromagnetic (EMF) fields, which may have detrimental effects to living organisms. The mechanical fluids such as lubricants may leak from the machinery, leading to some harmful pollution of the marine environment and seashores (Chen *et al.*, 2018b).

Parameter	Value	Symbol	Units
Installed capital cost	8,500	ICC	US$/kW
Annual operation and maintenance costs	170	O and M	US$/kW/year
Break-even point	15	BEP	Yrs
Plant unit cost of energy	0.15	UCOE	US$/kWh

Table III. Economic characteristics of an OTEC plant

Natural gas	Ocean thermal energy
It cannot be used again once it has been depleted, as it is a non-renewable source	It is a renewable energy resource, and it can replenish and hence has low probability of depletion
It can cause different environmental damages and pollution to the environment	It provides a clean and renewable source that has a low impact on the environment, thereby providing means for sustainable development
Cost of maintaining and managing a gas powered plant is relatively high	It has very low maintenance and management cost as compared to a gas powered plant
The cost of setting up a new gas powered plant is high, although it can be financed by the private sector	The cost of setting up an ocean thermal energy plant is exorbitant and can only be financed by federal government

Table IV. Comparison between natural gas and ocean thermal energy

4. Conclusion

We investigated the prospects, economic feasibility and impacts of OBRE in the West African region. An OTEC system is proposed, and analysis is done using Nigeria as a case study. Based on the study, we asserted that the adaptation of an OTEC system could potentially provide the energy required and solve the much needed challenge in electricity generation in the coastal regions of Nigeria. An OTEC provides numerous advantages and also guarantees secure and clean electricity for the sustainable future of Nigeria. It can also be used for other purposes such as desalination of water, agricultural purposes, among others. The initial capital cost to set up the project is high; however, it will provide a cost-effective generation and transmission, environmental improvement and stable energy supply to match the demand when compared with the conventional mode of electricity generation in West Africa. The initial high cost can also be significantly reduced by installing high capacities, instead of in small units and also through electrical connection to the nation-wide grid. The high initial cost also means that the project requires to be financed by the federal government of Nigeria. The result of this study can also be extended to other West African countries with similar ocean thermal energy potentials.

In the future work, we will consider the scenario in which the OTEC plant is used not only supply not only the local demand, but also satisfy the demand from other regions; therefore, the analysis of the distribution and transmission costs is necessary.

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