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Technoeconomic Analysis of Offshore Hybrid Power Systems' Distributed Energy Resources

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***Abstract*— In this paper, techno economic analysis of offshore hybrid power systems' distributed energy resources (DER) is presented. The study site is at Ibeno beach in Akwa Ibom state which is noted as the longest sand beach in West Africa covering about 2 km stretch of shoreline. The electric load demand profile of the users in the study site is determined and the sizing of each of the DER units is also carried out. Furthermore, the economic analysis is carried out. Particularly, the approach used for the economic analysis include the life cycle cost, total annualized cost and levelized cost of energy. The results show that the energy storage unit has more than 50% of the Total Net Present Cost (TNPC) of N168, 029,690 and the Cost of Energy (COE) of N 2,907.50. The least TNPC of N 11009500 is from the PV unit. Similarly, the least COE of N 190.5 is from the PV unit. Due to the heavy cost of the storage unit, the TNPC and COE of the system with and without the storage unit are compared and the results show that without the storage unit, the TNPC and COE of the system will be reduced be over 53%.**

Keywords*— Techno Economic Analysis, Offshore, Hybrid Power Systems, Distributed Energy Resources, Electric Load Demand, Economic Analysis, Levelized Cost of Energy

I. INTRODUCTION

Offshore sites, in most cases are remote locations that are away far from the national electric power grid. In that case, the electric power users in such sites must be supplied from alternative power sources. The choice of the power generating technology to be adopted for such sites depends on a number of factors. Generally, the diesel electric generator is the commonest alternative source of electric power in the developing countries like Nigeria [1,2,3,4]. Although the diesel electric generator is not a clean energy technology, it is popular because it is an established technology with low initial investment cost when compared to the clean energy technologies like solar photovoltaic (PV) energy and wind turbines. However, as advancement in the clean energy technologies continues to drive the cost down, there is growing adoption of such technologies [5,6,7,8,9,10].

In this study, a hybrid power system [11,12,13,14] for an offshore site located along the coastline of Atlantic ocean at Ibeno in Akwa Ibom State of Nigeria is studied. The hybrid power system is a microgrid which consists of distributed energy generating resources (DEGRs) along with the electric load and energy storage unit [15,16,17,18]. The DEGR includes the solar PV power unit, the wind turbine unit and the diesel electric generator unit. Each of the DEGR provides a fraction of the total load demand of the users.

Specially, the mathematical models for the sizing of each of the distributed energy resources (DER) are presented along with the economic analysis models. Specific commercially available sample components are selected for the implementation of the techno economic analytical models for each of the DER. Results are presented for a case where there is no storage unit and the results are compared to a case where the system has a storage unit. The idea presented in this paper is relevant for electric power supply in remote coastlines where recreational activities and fishing business and fish storage cold-room facilities are usually prevalent.

II. METHODOLOGY

A. The Case Study Load Profile and Meteorological Data

Ibeno Bar Beach is located at latitude 4.542 and longitude 8.009. It is reputed to be the longest sand beach in West Africa covering about 2 km stretch of shoreline. The beach is part of the West African border with the Atlantic Ocean. There some residential and commercial buildings that is located around the beach. For the part of the beach considered in this study, the electric load demand profile is given in Table 1. The load profile has a peak load of 79,170 watts or 79.17 kW which if it runs for 24 hours per day will amount to a daily energy demand of 1900.0kWh per day.

Table 1. The electric load demand profile of the case study site at Ibeno Bar Beach

S/N	End-Use Appliance	Quantity	Unit Power (W)	Total Unit Power (W)
1	Cold Appliances	43	450	19350
2	Fan	203	85	17255
3	Entertainment Appliances	46	75	3450
4	Lighting	547	30	16410
5	Cooking appliances	8	1500	12000
6	Pressing Iron	6	1000	6000
7	Washing appliances	5	119	595
8	Document Processing Appliances	14	43	602
9	Water Pump	3	400	1200
10	Miscellaneous	30	77	2310
			3779	79,17.00

The meteorological data of Ibeno Bar Beach is obtained from the NASA website and it consist of 22-years daily average of solar radiation on the horizontal plane (which is 4.27 kWh/m^2/day), daily average of ambient temperature (which is $29.08\,^{o}C$) and daily average of wind speed at an altitude of 10 m. (which is $9.7.0ms^{-1}$). The ambient temperature and wind speed are for the onshore location at Ibeno. The expression that is used to determine the offshore ambient temperature and wind speed from the onshore data values are given as follows [19];

$$T_W = 5.0 + 0.75(T_a)(1)$$

$$u_W = 1.62 + 1.17(u_a)(2)$$

where T_W and u_W are the modeled values of offshore ambient temperature and wind speed, while T_a and u_a are the measured values of onshore ambient temperature and wind speed respectively. When the expressions are used, the offshore ambient temperature and wind speed becomes;

$$T_W = 5.0 + 0.75(29.08\,^{o}C) = 27.35\,°C$$

$$u_W = 1.62 + 1.17(9.7.0ms^{-1}) = 13.0ms^{-1}$$

B. Sizing of the Offshore PV Array

The effect of ambient temperature and wind speed on the output of the PV array can be determined as follows;

$$P_S = P_{STC} f\left[1 + \alpha_p(T_c - T_{c,STC})\right](5)$$

Where the PV array cell temperature T_c can be determined as follows [20];

$$T_c = 0.943T_w + 0.095G_T - 1.528u_w + 0.3529(6)$$

where P_{STC} is the STC rated output of the PV module, α_p is the temperature coefficient of the module, T_c is the cell temperature, $T_{c,STC}$ is the STC cell temperature which is 25 $°C$,u_w is the offshore wind speed, T_w is the offshore ambient temperature and G_T is the effective solar irradiance incident on the PV array in $kWh \cdot m^{-2}\ per\ day$. Given that $T_a = 29.08\,^{o}C$, $u = 1.69\ ms^{-1}$ and $\mathrm{G_T} = 274\ \mathrm{Wm^{-2} per\ day}$, then, the cell temperature is obtained as;

$$T_c = 0.943(27.35\ ) + 0.095(274) - 1.528(13) + 0.3529 \\ = 32.3\ ^{o}C$$

When $T_c = 43.8\ ^{o}C$ is applied the PV power output becomes;

$$P_{CPV} = 280[1 + (-0.43/100)(32.3\ \ - 25)] \\ = 280[0.96864053] = \ 272.3\ W$$

Therefore, since the PV system supplies one-third of the entire load demand with peak power of 79,170 W, the number of modules required for the system is given as;

$$N_{CPV} = \frac{\left(\frac{79{,}170\ \ \mathrm{W}}{3}\right)}{272.3} = \frac{26390}{272.3} \approx 92\ modules$$

C. Sizing of the Offshore Wind Turbine

The wind turbine power output is given as;

$$P_w = a_w u^3 + a_w^{'} u^2 + a_w^{"} u(13)$$

Where u is the wind speed and $a_w, a_w^{'} \mathrm{and} a_w^{"}$ are coefficients. The selected wind turbine is BWC Excel 10kW model where its $a_w,\ a_w^{'} \mathrm{and} a_w^{"}$ are given as $0.0112, -0.008\ and - 0.0775$ respectively. For the offshore site $u_w = 13ms^{-1}$ and the turbine output power, $P_{OWT} = 9.5kW$. Also, the wind turbine supplies one-third of the load demand, hence the number of wind turbines needed is given as;

$$N_{OWT} = \frac{26.39}{9.5} = 2.77 \approx 3\ turbines$$

D. Sizing of the Diesel Generator Power Supply

With the peak power given as 79.17 kW which at power factor of 0.8 will amount to 98.9625 KVA, two 50 kVA diesel generator are used in this work. Specifically, the 50 kVA 400 ekW Caterpillar C15 Prime rated generator - Mantrac Unit, is selected.

E. Sizing of the Energy Storage

The energy storage is used to store about one-third of the daily energy demand which is given as ($\frac{1900kW}{3}$) = 634 kWh. The 210 kWh energy storage capacities Tesla Powerpack is selected. Then, the number of Tesla Powerpacks required for the storage is given as;

$$N_{ES} = \frac{\left(\frac{1900}{3}\right)}{210} \approx 3\, powerpacks$$

III. ECONOMIC ANALYSIS OF THE OFFSHORE MICROGRID DISTRIBUTED ENERGY RESOURCES

The approach used for the economic analysis include the life cycle cost, total annualized cost and levelized cost of energy. The economic approach based on the Total Net Present Cost (TNPC) and Cost of Energy (COE) is also developed for the Microgrid configuration considering the lifetime period and replacement costs of the individual Distributed Energy Resources (DER) units [21, 22].

The Total Net Present Cost (TNPC) is the sum-total of the Net Present Cost (NPC) of each DER unit. The NPC presents the value of all the costs the system incurs over its lifetime, minus the present value of all the revenue it earns over its lifetime. These costs include; initial (capital) cost, operations and maintenance (O&M) cost,

A. The Initial (Capital) Cost

Initial (capital) cost,IC_{CAP} of a DER component is the total installed cost of the component at the beginning of the project. For the entire microgrid,$IC_{CAP}$is given as [23]:

$$IC_{CAP} = \left(C_{PV} \times C_{UNIT,PV}\right) + \left(C_W \times C_{UNIT,W}\right) + \left(C_{ES} \times C_{UNIT,ES}\right) + \left(C_{FG} \times C_{UNIT,FG}\right) + C_O \quad (14)$$

where $C_{PV} and\, C_{UNIT,PV}$ are the total capacity (W) and unit cost (₦ /W) of the floating PV array respectively, $C_W\ and\ C_{UNIT,W}$ are the total capacity (W) and unit cost (₦ /W) of the wind turbine respectively; $C_{ES}\ and\ C_{UNIT,ES}$ are the total capacity (Wh) and unit cost (₦ /Wh) of the energy storage system respectively; $C_{FG}\ and\ C_{UNIT,FG}$ are the total capacity (W) and unit cost (₦/W) of the fuel generator respectively; and C_O is the total constant cost including the cost of civil works, installations and connections.

C. The Operations and Maintenance (O&M) Cost

The operations and maintenance (O&M) costs, $C_{O\&M}$ is simply the cost associated with operating and maintaining a DER unit. Most times, it is presented as an annual value except in the case of diesel generators. For the entire hybrid system, $C_{O\&M}$is given as [23];

$$C_{O\&M,hybrid} = C_{(O\&M)_o} \times \left(\frac{1+f_1}{k_d - f_o}\right) \times \left(1 - \left(\frac{1+f_o}{1+k_d}\right) L_p\right) \quad (15)$$

where f_1 s the inflation rate for operations, k_d is the annual real ineterst, L_p is the system lifetime period in years, $C_{(O\&M)_o}$ is the operation and maintenance cost in the first year. It can be given as a fraction 'k' of the initial capital cost,IC_{CAP} is given as;

$$C_{(O\&M)_o} = kIC_{CAP} \quad (16)$$

Other costs utilized in the computation of NPC are fuel cost, C_F and the cost of buying power from the Utility, C_G. However, the IC_{CAP} and $C_{O\&M}$ for each DER component in this work have been given. On that note, NPC is calculated for each component. For the Microgrid model implemented in this work, NPC and TNPC are given as follows [21];

$$NPC_j = \left(IC_{CAP} \times N_j\right) + \left(C_{O\&M} \times R \times N_j\right) + \left(C_F \times R \times N_j\right) + \left(C_G \times R\right) \quad (17)$$

$$TNPC = NPC_S + NPC_W + NPC_F + NPC_{ES} \quad (18)$$

where $= S, W, F, ES$ ... , are the types of DER unit; that is, S is the solar PV, W is the wind turbine, F is the diesel generator and ES is the energy storage system. Other important items are the initial capital cost,IC_{CAP}, the O&M cost, the $C_{O\&M}$, the fuel cost, C_F and the cost of buying power from UtilityC_G. R is the lifetime of the unit and N_j is the number of DER unit used.

C. Cost of Energy (COE)

The Cost of Energy (COE) is the average cost of energy per kWh of useful electrical energy produced by each unit, and it is given as [24] ;

$$COE = \frac{i(1+i)^R \times NPC}{D\{(1+i)^R + 1\}} \quad (19)$$

where i is the interest rate, R is the lifetime period and $D = 261 \times \sum_{h=1}^{24} P_{wd}(h) + 104 \times \sum_{h=1}^{24} P_{wed}(h)$ is the total electrical load served in kWh per year, making P_{wd} and P_{wed} the load curves for weekday and weekend day, respectively.

D. Results and Discussion on the Lifespan Cost Analysis of the System Components

Presently, the cost for a Bergey Excel-S - 10 kW wind turbine is ₦ 9,596,050.00, excluding installation and salvage costs, which are estimated to add 40% to the figure for offshore (coastline) installations. Hence, the offshore wind turbines has an initial capital cost of ₦ 13434470 (that is, 1.4(₦ 9,596,050.00). That means, for the wind turbine DER unit,$IC_{CAP} =$ ₦13434470 . Based on industry data, the annual O&M cost for wind turbines is taken to be 1.5% of their initial cost. This is equivalent to ₦ 201517.05 (that is, 0.015 (₦ 13434470) for the Bergey Excel-S-10kW wind turbine installed in an offshore location. That means, for the wind turbine DER unit, $C_{O\&M} = \text{₦}201517.05$.

The Global Solar PowerFlex photovoltaic array cost is ₦109,500.00 per PV module, including the installation and the stand cost, and an extra ₦ 4,000 for each module for offshore installations and mooring system. This gives a total of ₦113,500.00 per PV module. That means, for the PV DER unit, $IC_{CAP} = \text{₦}113{,}500.00$. PV panels and batteries are virtually maintenance free.

The capital cost of each CAT 50kVA C15 diesel generator is ₦ 3060000 including cost of installation, civil work and connections. That means, for each of the two diesel generators, the $IC_{CAP} = \text{₦}\,3060000$. Also, for the diesel generators, the annual O&M and incidental expenses is 5% of the initial generator cost of each of the diesel generators; this is equivalent to $C_{O\&M} = \text{₦}$ 153000. In Akwa Ibom, diesel price from bulk retailers is currently ₦222.22 per litre. Hence, the fuel cost per kWh is ₦ 126.98, which brings the sum of fuel cost to ₦80420.67, per day per diesel generators.

The capital cost of the Tesla Powerpack is ₦ 140,645 per kWh. Each storage module can store up to 210 kWh of energy with a bi-directional 250 kW inverter, altogether for a total of 634kWh (that is one-third of the total 1900 kWh per day) the total cost is ₦ 89168930.

The life span of the diesel generators is taken as 20 years, with 2 major overhauls in the middle of its lifetime (their cost is included in the maintenance). Wind turbines have a manufacturer guaranteed life of 20 years. In most literature, the lifespan of a PV panel is taken as 25 years, and that is the value used in this study. The lifespan of the Tesla Powerpack ranges between 2,500 and 4,500 full cycles depending on operating conditions; so, it is taken as 3,500 cycles, which is same as 15 years.

E. Economic Analysis for the DER Units in the Offshore Hybrid System

Each of the DER is providing one-third of the total energy demand, which is about $\frac{1900}{3}$ kWh/day = 633.33 kWh/day and in a year it will amount to 365(633.33 kWh/day) = 231166.67 kWh/year. The cost of energy for each DER unit is derived.

i. **Offshore PV system** $(IC_{CAP} = \text{₦}113{,}500.00$ and N_{FPV} = 97)

$$NPC_{SW} = (IC_{CAP} \times N_{FPV}) = (113{,}500.00\ \times 97) = \text{₦}\,11009500$$

$$\therefore\ COE_{SW} = \frac{4(1+4)^{25}\times 11009500}{((1+4)^{25}-1)(231166.67\,)} = \text{₦}190.50 \text{ per kWh}$$

ii. **Offshore wind turbines (WTs).**

$$NPC_{WW} = (IC_{CAP} \times N_{OWT}) + (C_{O\&M} \times R \times N_{OWT}) = (13434470 \times 3) + (243517.05\ \times 20 \times 3) = \text{₦}\ 52394433$$

$$\therefore\ COE_{WW} = \frac{4(1+4)^{20}\times 52394433}{((1+4)^{20}-1)(231166.67\,)} = \text{₦}906.6088 \text{ per kWh}$$

iii. **Offshore energy storage**

$$NPC_{ES} = \text{₦}89168930$$

$$\therefore\ COE_{ES} = \frac{4(1+4)^{15}\times 89168930}{((1+4)^{15}-1)(231166.67\,)} = \text{₦}1542.938 \text{ per kWh}$$

iv. **Offshore diesel generator, where the $\mathbf{N_{FG} = 2}$**

$$NPC_{FG} = (IC_{CAP} \times N_{FG}) + (C_{O\&M} \times R \times N_{FG}) + (C_F \times R) = (\,3060000\ \times 2) + (153000 \times 20 \times 2) + (126.98 \times 20 \times 2) = \text{₦}15456827$$

$$\therefore\ COE_{FG} = \frac{4(1+4)^{20}\times 15456827}{((1+4)^{20}-1)(231166.67\,)} = \text{₦}267.4577 \text{ per kWh}$$

Therefore, the total net present cost and total cost of energy for the offshore hybrid system is given as;

$$TNPC_w = \text{₦}\,11009500 + \text{₦}\ 52394433 + \text{₦}\,15456827\ + \text{₦}\,89168930 = \text{₦}168{,}029{,}690.00$$

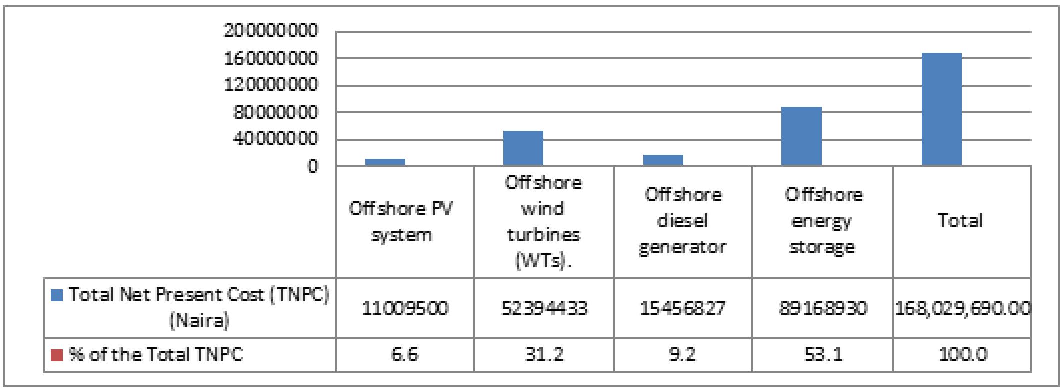
$$COE_W = \text{₦}\,190.50\ + \text{₦}\,906.6088\ + \text{₦}\,267.4577\ + \text{₦}\,1542.938\ = \text{₦}2{,}907.50 \text{ per kWh}$$

Without energy storage the results will be;

$$TNPC_w = \text{₦}\,11009500 + \text{₦}\ 52394433 + \text{₦}\,15456827 = \text{₦}78{,}860{,}760.00$$

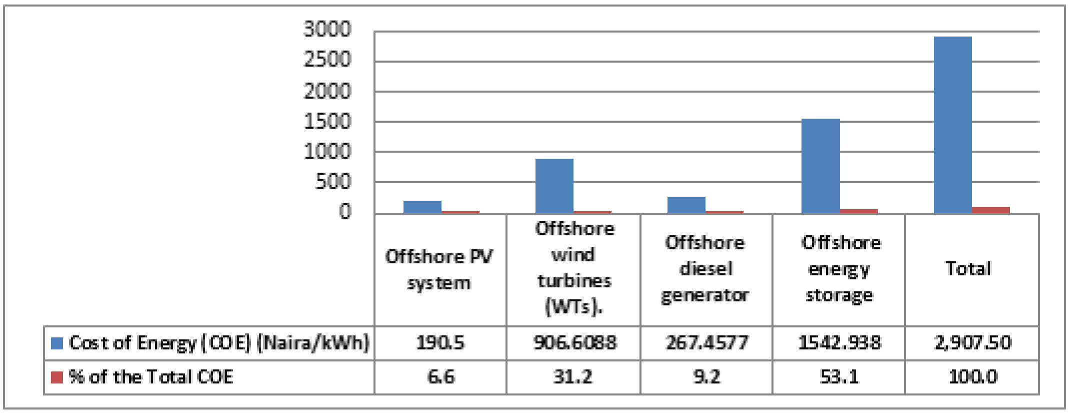
$$COE_W = \text{₦}\,190.50\ + \text{₦}\,906.6088\ + \text{₦}\,267.4577 = \text{₦}1{,}364.57\ \text{ per kWh}$$

The bar chart of the Total Net Present Cost (TNPC) is shown in Figure 1. The results in Figure 1 show that energy storage has more than 50% of the TNPC of ₦168,029,690. The least TNPC of ₦ 11009500 is from the PV unit. Similarly, the bar chart of the Cost of Energy (COE) is shown in Figure 2. The results in Figure 2 show that energy storage has more than 50% of the COE of ₦ 2,907.50. Also, the least COE of ₦ 190.5 is from the PV unit. Due to the heavy cost of the storage unit, the TNPC and COE of the system with and without the storage unit are compared in Figure 3 and Figure 4 respectively. The results in Figure 3 and Figure 4 show that without the storage unit, the TNPC and COE of the system will be reduced be over 53%.



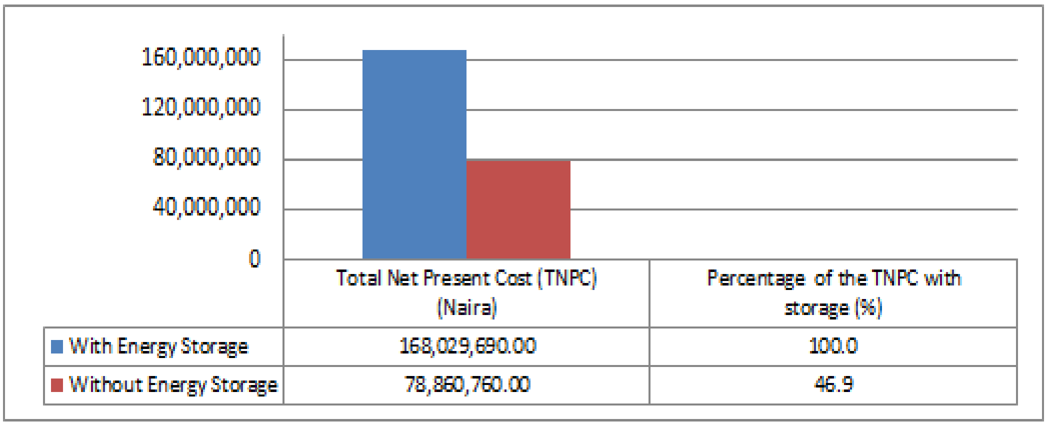
	Offshore PV system	Offshore wind turbines (WTs).	Offshore diesel generator	Offshore energy storage	Total
🟦 Total Net Present Cost (TNPC) (Naira)	11009500	52394433	15456827	89168930	168,029,690.00
🟥 % of the Total TNPC	6.6	31.2	9.2	53.1	100.0

Figure 1. The Bar chart of the Total Net Present Cost (TNPC)



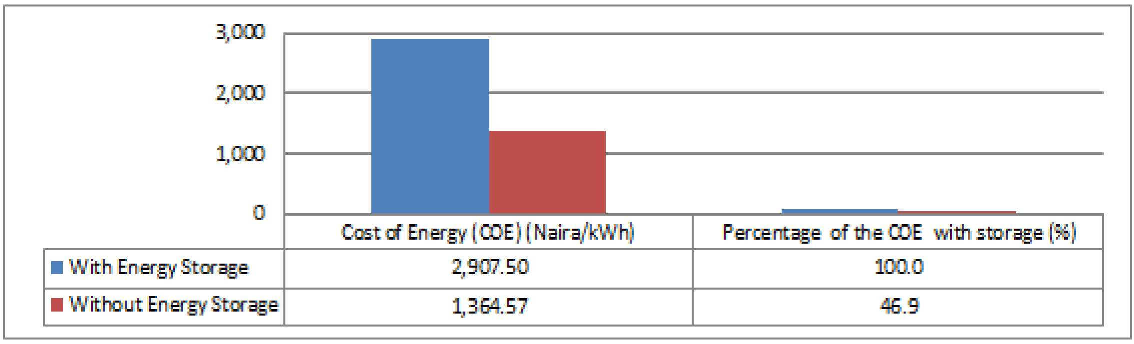
	Offshore PV system	Offshore wind turbines (WTs).	Offshore diesel generator	Offshore energy storage	Total
🟦 Cost of Energy (COE) (Naira/kWh)	190.5	906.6088	267.4577	1542.938	2,907.50
🟥 % of the Total COE	6.6	31.2	9.2	53.1	100.0

Figure 2. The Bar chart of the Cost of Energy (COE)



	Total Net Present Cost (TNPC) (Naira)	Percentage of the TNPC with storage (%)
🟦 With Energy Storage	168,029,690.00	100.0
🟥 Without Energy Storage	78,860,760.00	46.9

Figure 3. The Bar chart of the Total Net Present Cost (TNPC) with and without the energy storage



	Cost of Energy (COE) (Naira/kWh)	Percentage of the COE with storage (%)
🟦 With Energy Storage	2,907.50	100.0
🟥 Without Energy Storage	1,364.57	46.9

Figure 4. The Bar chart of the the Cost of Energy (COE)with and without the energy storage

IV. CONCLUSIONS

Technical and lifecycle cost analysis were conducted for offshore hybrid power system that has PV , wind and diesel generators as the power source and also includes a storage unit. The site of the power system is at Ibeno beach which is part of the coastline of the Atlantic Ocean. In the technical analysis, the sizing of the component distributed energy resources (DER) is presented and in the economic analysis, life cycle cost analysis is presented for each of the DER. Eventually, the overall system Total Net Present Cost (TNPC) and Cost of Energy (COE) are determined and compared for a case where the system operate with and without energy storage. The results show that the energy storage accounts for over 50% of the system Total Net Present Cost (TNPC) and Cost of Energy (COE).

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