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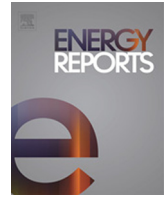
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Economic cost evaluation on the viability of offshore wind turbine farms in Nigeria



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ABSTRACT

The paper presents an economic cost evaluation on the feasibility of offshore wind turbine (OWT) farms development in Nigeria, using a 500 MW OWT farm as an incident study. A developed model was used to evaluate the economic cost of the OWTs at different phases of the project. Additionally, the effect of the cost drivers at the changed phases of the OWTs was studied correspondingly. Results obtained showed that over 50% of the OWT project cost emanated from CAPEX while a value less than 50% came from OPEX. However, further analysis indicates at maximum power of 4 MW a 4.95% diminution in LCOE. For comparable power rating (PR) between $5 \leq PR \leq 6$ MW, a 2.7% reduction in LCOE exists. Cost stability was apparent at a growth of WT between $300 \leq WT \leq 500$ MW. The study also observed a decrease in LCOE for all development stages of the OWT while a decrease in the CMS detectability was considered marginal. Subsequently, it can be inferred that Nigeria has the potential for OWT farm expansion. However, the demonstrated model was appropriate for handling preliminary variations in OWT studies.

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1. Introduction

Over the past years, Nigeria had faced insufficient electricity supply due to poor infrastructure as well as inadequate gas supply to power generating turbines. The latter is culminated by youth restiveness especially in the regions where the power generating stations are domiciled. Furthermore, apart from these factors, the dwelling oil reserves and the environmental complications arising from fossil fuel utilization necessitates the need for greener energy development (Abam and Ohunakin, 2015). Additionally, onshore wind power in recent times is receiving wider acceptability as an alternative for fossil energy derivatives. For example, the Global Wind Energy Council (GWEC) in 2014 has projected a 3.4% annual increase with a cumulative increase of 14.9% and growth installed capacity of 47 GW. South Africa, Mexico, and Ethiopia all developing economies have projected an increase of 9 GW installed capacity by 2030, 2 GW by 2024 and 7 GW in 2030, respectively (GWEC, 2014; Pineda et al., 2014).

Moreover, development and application of offshore wind turbine farm appears to be increasing across the world particularly in the developed economies. In Europe, for instance the installed

capacity of OWTs has grown rapidly in the last decade with an average annual growth of 50% (Pineda et al., 2014; Esteban et al., 2011; Green and Vasilakos, 2011). OWTs have great potentials and advantages over onshore wind turbines, these include high power rating, high yield energy, high offshore wind and unlimited space which make the installation of bigger OWT possible. Nonetheless, the drawback of the OWT technology is the additional cost that has to do with capital cost, operation and maintenance cost (O&M). The additional cost is associated with customized vessels, transmission system and weather (Bilgili et al., 2011; Dicorato et al., 2011; Madariaga et al., 2012). Likewise, OWTs farm or project development is technically and economically involving. For this reason, they require economic cost evaluation tools for adequate analysis. One of the most applicable tools, is the levelized cost of energy (LCOE) model. The LCOE relates the energy yield from the turbines with the generating cost. This measure takes care of the cost from the predevelopment phase to the decommissioning stage of the OWT project. By this, the key areas where cost can be reduced in the different phases of the OWT project are identified. Additionally, the investment decision-making process for a possible cost before purchase is made flexible (Madariaga et al., 2012). At present, Nigeria appears to be into the vortex of energy crisis, a situation that has generated economic disproportion and thus slowed industrialization (Abam and Ohunakin, 2015). Optimal energy utilization through a viable

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energy mix framework is opined as an effective measure to ensure energy security in Nigeria. The present study therefore aims at adopting the framework in [Madariaga et al. \(2012\)](#) to economically estimate the viability of all the associated OWT costs and its implementation in Nigeria. The key cost drivers for the application of the OWT technology will be identified. Moreover, the upshot from the study may constitute the basis for preliminary cost reduction to any agency, governments and organizations, who intend to adopt the OWT technology for development specifically in Nigeria

2. Methodology

The methodology adopted in this study includes the cost breakdown structural approach and the simple leveled cost of energy method ([Bilgili et al., 2011](#); [Gielen, 2012](#); [Teegen et al., 2012](#)). The latter is used in evaluating the life cycle cost (LCC) of each phase of the OWT farm project. The methodology for the economic cost evaluation was divided into five project stages which include: the predevelopment and consenting (P&C), production and acquisition (P&A), installation and commissioning (I&C), operation and maintenance (O&M), and decommissioning and disposal (D&D). The general expression for the economic viability cost (EC_v) of an OWT farm project is expressed in Eq. (1) ([Green and Vasilakos, 2011](#); [Bilgili et al., 2011](#)).

$$EC_v = \sum (C_{P\&C}, C_{P\&A}, C_{I\&C}, C_{O\&M}, C_{D\&D}) \quad (1)$$

where C is the total cost per year while the present value and the leveled cost of energy (LCOE) are presented in Eqs. (2) and (3) ([Gielen, 2012](#); [Arwas et al., 2012](#)).

$$Pv(x) = \frac{x}{(1+d)^n} \quad (2)$$

$$LCOE = \frac{\sum \frac{C_n}{(1+d)^n}}{\sum \frac{E_n}{(1+d)^n}} \quad (3)$$

where d is the discount rate, and n is the year the revenue or cost takes place

2.1. Predevelopment and consenting

It takes about five years to develop any OWT project afore the time of installation. During this period, a lot of paperwork including, the cost implications, and legal framework are established to certify the feasibility of the OWT project. The cost segment entails: the cost of managing the project C_{pm} ; the legal authorization process cost C_{leg} ; the cost of surveys carried out C_{sur} ; the cost of engineering activities C_{eng} ; as well as the contingencies cost, C_{com} . The component cost are defined in Eq. (4) ([Dicorato et al., 2011](#); [Castro-Santos and Diaz-Casas, 2014](#); [Offshore Design Engineering Ltd., 2007](#)).

$$C_{P\&C} = \sum (C_{pm}, C_{leg}, C_{sur}, C_{eng}, C_{com}) \quad (4)$$

where C_{pm} is assumed to be 3% of the total capital expenditure.

The cost of surveys to be conducted and installation capacity of the OWT is given by Eqs. (5) and (6) ([Bjerkseter and Agotnes, 2013](#); [BVG Associates, 2010](#); [Kaiser and Snyder, 2012](#))

$$C_{sur} = IC \left[\sum (C_{sur_e}, C_{sur_c}, C_{sur_s}) \right] + C_{sur_m} \quad (5)$$

$$IC = PR \left[\sum_{i=1}^n N_{WTi} \right] \quad (6)$$

where C_{sur_e} , C_{sur_c} , C_{sur_s} and C_{sur_m} are the environmental, coastal processes, sea bed, and met-ocean survey costs while N_{WTi} is the network produced by the offshore wind turbines and PR is the power rating of OWT in the wind farm.

Eq. (7) expresses the cost of engineering activity which include the material selection and structural design of the OWT project.

$$C_{eng} = \sum (C_{eng_m}, C_{eng_v}) \quad (7)$$

where C_{eng_v} represents the cost associated with the critical verification by a third party and C_{eng_m} represents the main engineering activities cost dependent on the OWT project size ([Bjerkseter and Agotnes, 2013](#); [Maples et al., 2013](#)). The C_{eng_v} is a linear function of the installation capacity and it can be expressed as in Eq. (8) ([Garrad Hassan, 2013](#); [Tavner, 2013](#))

$$C_{eng_m} = \left[\sum (C_{base}, C_{eng_t}) \right] \times (IC - 108) \quad (8)$$

where C_{base} is the independent base cost, set at a base case of 108 MW offshore wind farm ([Offshore Design Engineering Ltd., 2007](#)).

2.2. Procurement and acquisition

Wind turbine generator (WTG), the support structure/foundation, the power transmission system (PTS) and the monitoring systems are the key components of the OWTs. Therefore, the costs associated with these components makes up the cost for the procurement and acquisition stage. This cost is expressed in Eq. (9). Their detailed expressions are contained in [Dicorato et al. \(2011\)](#), [Gielen \(2012\)](#), [BVG Associates \(2010\)](#), [Kaiser and Snyder \(2012\)](#), [Maples et al. \(2013\)](#), [Garrad Hassan \(2013\)](#) and [Tavner \(2013\)](#).

$$C_{P\&A} = \sum (C_{WT}, C_f, C_{PTS}, C_{mon}) \quad (9)$$

where

C_{WT} = procurement cost of the OWT sub-assemblies

C_f = procurement cost of the support structure/foundation

C_{PTS} = procurement cost of the electrical power transmission systems

C_{mon} = procurement cost of the systems used to monitor the OWT farm

2.3. Installation and commissioning

This stage has to do with all the allied installation works of the OWT beginning from the time the procured components are delivered to the commissioning of the OWT. The cost associated with the installation and commissioning stage is expressed as:

$$C_{I\&C} = \sum (C_{I\&Cport}, C_{comp}, C_{com}, C_{I\&Cins}) \quad (10)$$

where:

$C_{I\&Cport}$ = the cost incurred in the port,

C_{comp} = the component installation cost,

C_{com} = the cost of commissioning the OWTs and electrical system

$C_{I\&Cins}$ = the cost of construction insurance.

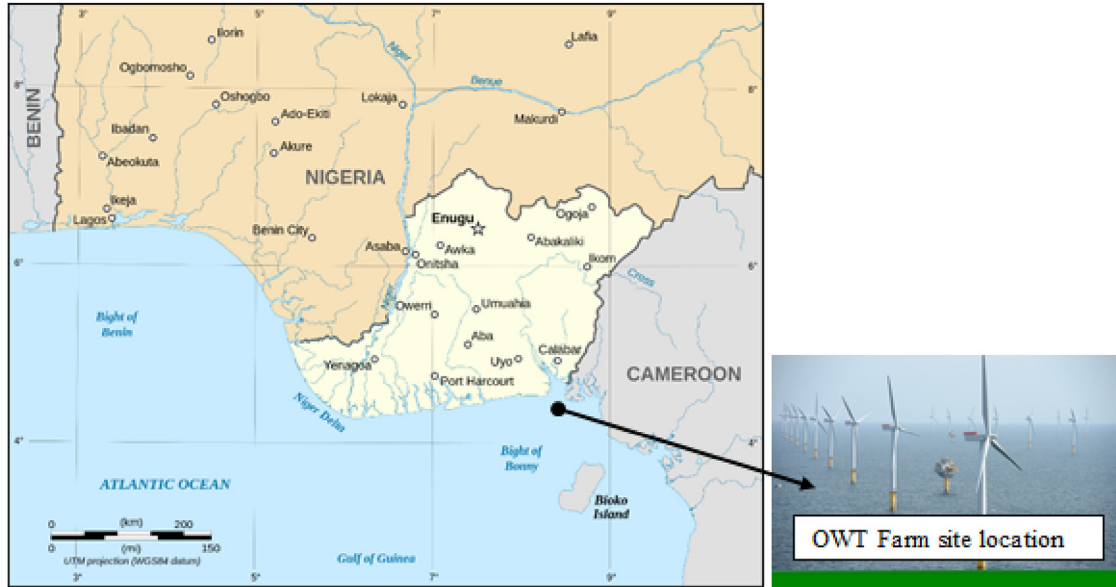


Fig. 1a. Map showing the point in Nigeria for the proposed OWT farm site.

2.4. Operation and maintenance

In the operation and maintenance stage the longevity and operational life of the OWTs is considered. The cost associated with O&M is expressed in Eq. (11) defined as the operational cost (C_O) and maintenance cost (C_M) further expanded in Eqs. (12) and (13) respectively.

$$C_{O\&M} = \sum (C_O, C_M) \quad (11)$$

$$C_O = \sum (C_{lea}, C_{ins}, C_{transm}) \quad (12)$$

$$C_M = \sum (C_{M_{fix}}, C_{M_{var}}) \quad (13)$$

C_{lea} = cost of seabed rentals paid to government or host community

C_{ins} = insurance

C_{transm} = transmission charges

$C_{M_{fix}}$ and $C_{M_{var}}$ are the respective fixed and variable cost dependent on the types of maintenance activities undertaken.

2.5. Decommissioning and disposal

The decommissioning and disposal stage of the OWT project is expressed in Eq. (14). The stage describes the processes involved when the OWT complete its duty cycle or service life. One of which is the cost of decommissioning C_{dcm} . Others are the cost of waste management C_{wm} the cost of clearing the site per unit area C_{sc} and the cost of post monitoring activities C_{postM} (Arwas et al., 2012; Kaiser and Snyder, 2012; Department of Energy & Climate Change, 2011).

$$C_{D\&D} = \sum (C_{dcm}, C_{wm}, C_{sc}, C_{postM}) \quad (14)$$

2.6. Estimation of annual wind speed

The mean wind speed at 100 m height above sea level was evaluated using Eq. (15).

$$V_w(h) = V_{10} \times \left(\frac{h}{h_{10}} \right)^\alpha \quad (15)$$

where V_{10} is the mean speed of the site at studied height $h_{10} = 10$ m, α is the Hellman exponent for stable air above open water surface taken as 0.273 (Heier, 2005).

3. Case of study

The case study area for the OWT farm was applicable to one of Nigeria's deep sea located in the coastal region of Calabar, South-south Nigeria, bordered by the Republic of Cameroon (Fig. 1a). The modeled equations were applied on 100 OWTs with a generating capacity of 5 MW each. Additionally, the generating capacity of the OWT farm was 500 MW. The economic cost models used for the evaluation process is based on the five stages discussed in Levitt et al. (2011), Howard (2012) and Armada Espinosa de los Monteros (2014). A presentation of the design specifications of the baseline OWT based on the applied model is presented in Table 1. However, the following key assumptions were considered during the evaluation process. (1) A 2% value of the gross revenue representing the seabed lease is to paid to the Government. (2) The transmission charges is collected by the Nigerian Electricity Regulatory Commission (NERC). (3) A 33 kV array cables, a 500 MW HVAC OS and 220 kV export cables constitute the electrical system calculated from ($L_1 = 1.6065 N_{WT} - 16.065$). (4) 90% CMS detectability was fixed. (5) A constant failure rate was also used to calculate the Corrective maintenance cost. (6) It is only lease and charges that was calculated for the five year warranty period. The O&M insurance to be paid to the developer was not considered for the warranty period. (7) During the decommissioning stage, all the materials are processed and conveyed to the nearby scrapyard or landfill. (8) The towers of the OWT, the substructures, and other auxiliary components auctioned as scrap. (9) 60% recovery rate is expected from the hubs sales, while the remaining 40% alongside the array cables are deposited in the nearby landfill. (10) 9.24% discount rate was used for the calculation.

4. Results and discussion

The economic cost evaluation of the developed model was carried out and the key cost drivers for the OWT farm development identified. The cost distribution of each OWT project stage from P&C to D&D is presented in Fig. 1b. However, the results obtained indicate that about 55% of the OWT project being the highest cost,

Table 1

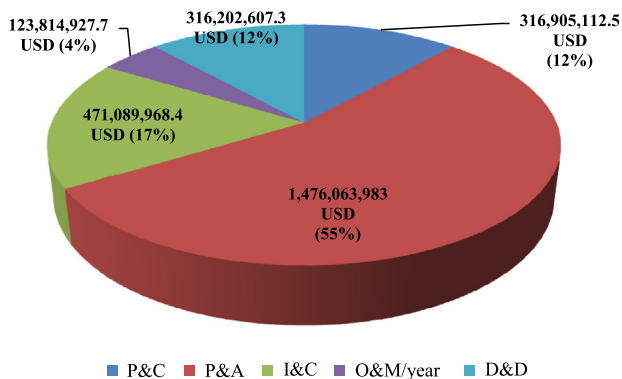
Baseline OWT farm configuration adopted for Nigeria from [Abam and Ohunakin \(2015\)](#) and [Levitt et al. \(2011\)](#).

Parameter	Symbol	Configuration	Unit
Number of wind turbines	N_{WT}	100	Units
Rated power	P_R	5	MW
Total installed capacity	IC	500	MW
Distance to port	d_{port}	40	km
Distance to onshore grid connection	d_{gridon}	10	km
Distance to offshore grid connection	$d_{gridoff}$	40	km
Water depth	WD	45	m
Operational life	L	20	years
Hub height	h	100	m
Annual mean wind speed at 100 m height	V_w	10.58	m/s
Rotor diameter	d	126	m
Foundation	–	Jacket	–
Gross load factor	–	0.535	%
Losses	$\sum losses$	0.141	%

Table 2

Distribution of cash flow for the five economic evaluation stages.

Year	Weighted investment distribution over the years									
Investment year	0	1	2	3	4	5	6–9	10–24	25	
Operational year	–4	–3	–2	–1	0	1	2–5	6–20	21	
Stage										
Developing and consenting	34%	2%	2%	21.5%	40%	0.271%	0%	0%	0%	0%
Procurement and acquisition	0%	0.09%	16.25%	37.29%	43.37%	2.88%	0%	0%	0%	0%
Installation and commissioning	0%	1.66%	1.66%	32.47%	61.41%	2.80%	0%	0%	0%	0%
Operation and maintenance	0%	0%	0%	0%	0%	46%	46%	100%	0%	0%
Decommissioning and disposal	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%

**Fig. 1b.** Cost distribution of each OWT project stage.

emanated from P&A. The reason is due to the high cost of procuring the key components of the OWTs such as WTG, PTS, support structure/foundation and the condition monitoring systems. Other project cost stood at 17% for I&C, 12% for P&C, 4% for O&M/year and 12% for D&D. [Table 2](#) depicts the distribution of the cash flow for the five studied economic stages at a 25 year period of the OWT farm project. This include 5 years of construction and 20 years of OWT operational life. The OWT farm will commence full operation from the 10th to 24th year, while 46% of its operation will be from the 5th to the 9th year of investment.

[Fig. 2\(a\)](#) presents a detailed cost distribution regarding capital expenditure (CAPEX). The CAPEX comprises the P&C, P&A and I&C project stages with an overall cost of USD 4528.125/kW. Conversely, it is observed that the key drivers of the capital cost of the OWT farm project as applied in Nigeria were the WTGs, installation, and the support structure/foundations. Their respective costs disparities exist at 29%, 19% and 25% in that order. Comparing the cost of the WTGs obtained in Nigeria with that obtained elsewhere, the cost difference was approximated at 10.63% higher than that obtained in [Armada Espinosa de los Monteros \(2014\)](#). Further comparison shows a 14.4% and 8.87% was

obtained by [Tegen et al. \(2012\)](#) and [Levitt et al. \(2011\)](#) in 2010 and 2012 respectively.

[Fig. 2\(b\)](#) shows a detailed cost distribution regarding operational expenditure (OPEX). The OPEX comprise the O&M only while the D&D remains a non-component of OPEX and CAPEX since the D&D comes after the OWT project. The annual OPEX obtained in Nigeria was estimated at USD 246.875/kW/yr. The key cost drivers of the OPEX were the cost related to the maintenance (which includes the cost of port, onshore task, the fixed vessel, preventive and corrective maintenance) and constituted about 45% of the OPEX. Other cost drivers of the OPEX, include the transmission charges, lease, and operational insurance, which constitute about 44%, 2%, and 11% of the OPEX, respectively. The value of OPEX obtained in this study was at close approximation with that obtained by [Levitt et al. \(2011\)](#), but differ slightly with the results of [Tegen et al. \(2012\)](#) and [Bjerkseter and Agotnes \(2013\)](#). However, this was because ([Tegen et al., 2012](#); [Bjerkseter and Agotnes, 2013](#)) did not take into cognizance the transmission charges in the evaluation process of the OPEX.

[Fig. 3](#) presents the distribution of the LCOE according to the OWT farm project stages. The yield energy output, the gross load factor, and the losses were used to evaluate the LCOE. The obtained LCOE was 190.5 USD/MWh while the availability of the downtime during the operational stage was 96.87% with OWTs generating at a capacity of 2,095,213 MWh/year. The study shows that about 48% of the budget for the OWT farm project will be spent in the P&A phase.

4.1. Sensitivity analysis

The sensitivity analysis carried out was to identify the projected trend against the cost drivers. The studied parameters were: the power rating of the OWTs, the number of wind turbines, the discount rate and the CMS maintenance improvements. [Fig. 4\(a\)](#) depicts the effect of the WT power rate on LCOE. Furthermore, the increase in power rating of the WT results to a decrease in LCOE, O&M and I&C are got. For example, an increase in power

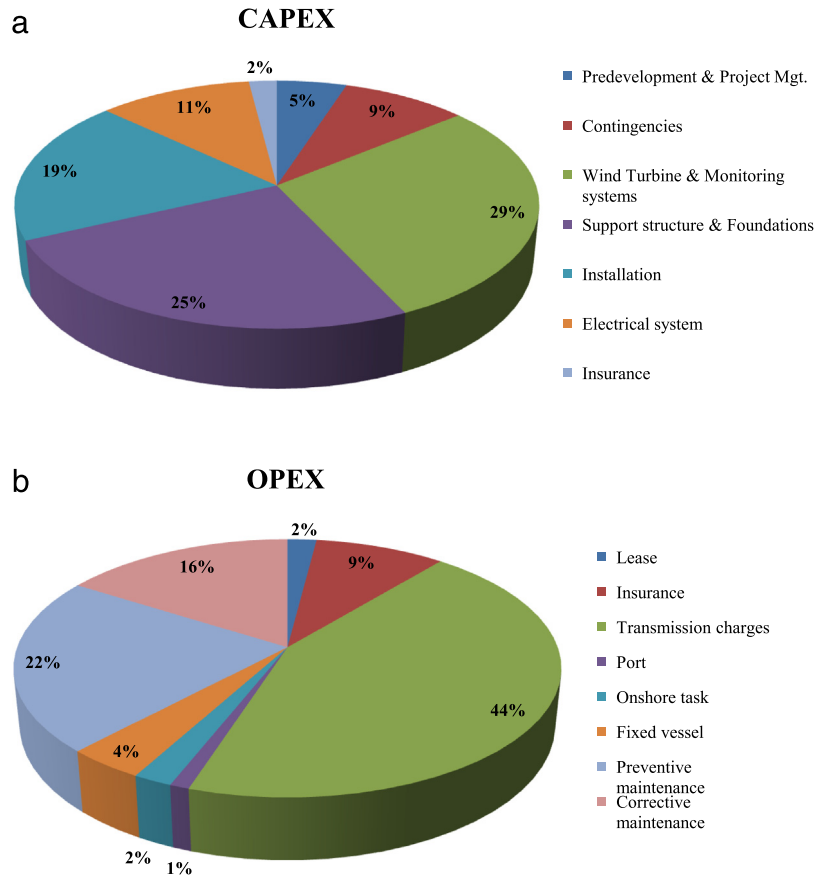


Fig. 2. (a) CAPEX distribution, (b) OPEX distribution.

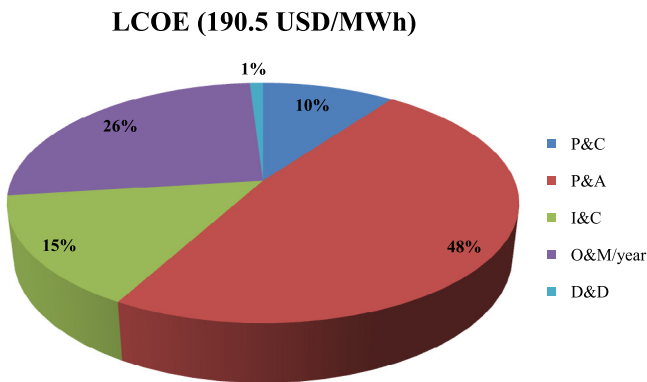


Fig. 3. Result of the LCOE obtained from the OWT baseline model.

rating from 2 to 4 MW led to a 4.95% decrease LCOE. Also, at ratings >5 MW <6 MW design power a 2.7% reduction in LCOE was obtained, indicating the cost decreases with turbine increase capacity.

The variation in LCOE with some WTs is presented in Fig. 4(b). The shows a sharp decrease of 20% in LCOE, which corresponds to a 40% increase in WTs. The LCOE continued to decrease significantly at over 80% stabilizing between 300 and 500 WTs increase. Reduction in LCOE would occur in all stages of the project except the O&M stage. For optimum reduction in cost during the O&M stage, maintenance strategies should be a top priority for the different sizes of the OWT farm.

Fig. 5(a) describes the effect of project funding on LCOE evaluated in the baseline model regarding discount rate. It is observed a 1% reduction in the discount rate led to a 5.5% decrease in the LCOE. The latter exist in similar studies (Arwas et al., 2012)

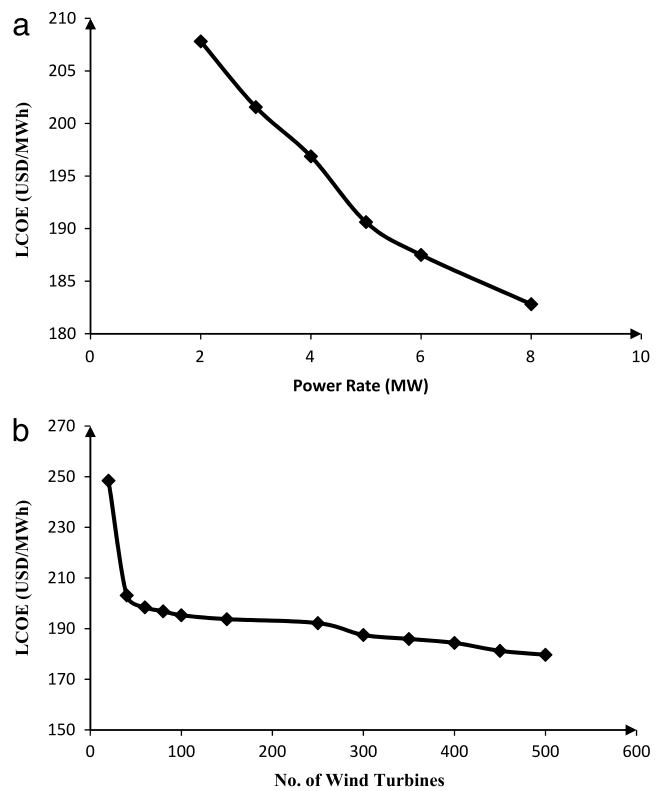


Fig. 4. Sensitivity result for (a) Effect of WT power rate on LCOE. (b) Effect of number of wind turbines on LCOE.

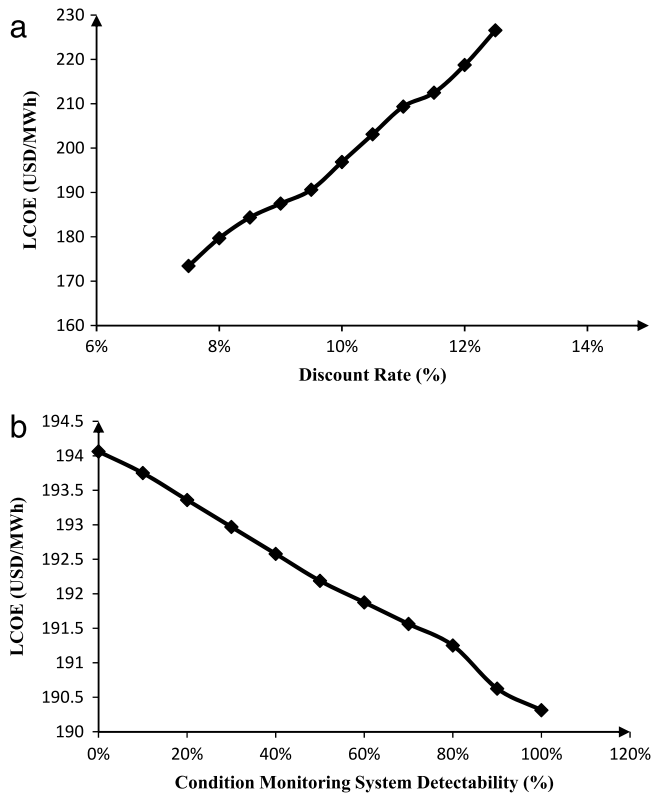


Fig. 5. Sensitivity results for (a) Effect of CMS detectability on LCOE. (b) Effect of Discount rate on LCOE.

where a 5.3% and 6% decrease in LCOE was obtained for the same scenario. It can be inferred that reducing the project cost will increase the project viability, investment rate and to some extent, the stability of the project.

Additionally, Fig. 5(b) presents the variations in CMS detectability with LCOE. The results indicate a 20% improvement in CMS detectability for a 1.48% reduction in LCOE. For all increase in CMS detectability, a decrease in LCOE is observed. Nonetheless, reduction in the CMS detectability may be insignificant in the O&M stage since OWT farm projects are always capital intensive (Armada Espinosa de los Monteros, 2014). Subsequently, there may exist possibilities for cost reduction during the operational life of the OWTs (see Fig. 5).

5. Conclusion

The economic cost evaluation on the viability of offshore wind turbine farms in Nigeria was considered. A mathematical model was developed to evaluate the latter which was actualized in five OWT project stages using a 500 MW OWT farm. The following conclusions were made: About 55% of the OWT cost came from P&A due to the high cost of procuring the key components of the OWTs, while other project costs exist at 17%, 12%, 4% and 12% for I&C, P&C, O&M, and D&D respectively. An overall cost of USD 4528.125/kW was obtained for the CAPEX project stages with its key drivers WTGs, installation, and the support structure/foundations having a cost share of 29%, 19% and 25% in that order. The annual OPEX was estimated at USD 246.875/kW/yr of which 45% was for OPEX cost

related to the key maintenance drivers while transmission charges, lease and operational insurance, were approximated at 44%, 2%, and 11% of the OPEX, respectively. The sensitivity analysis shows that an increase in power rating from 2 to 4 MW results to a 4.95% decrease in LCOE. For similar ratings >5 MW <6 MW design power a 2.7% reduction in LCOE was attained. The variation in LCOE with some WT's stabilizes between 300 and 500 WT's increase while the reduction in LCOE was found to occur in all stages of the project except in the O&M stage. The variations in CMS detectability with LCOE indicate a 20% improvement in CMS detectability for a 1.48% reduction in LCOE. However, reduction in the CMS detectability was found insignificant in the O&M stage. The model was most suitable for handling preliminary OWT studies.

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