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Evaluating the viability of WindPACT-1.5 MW HAWT for Offshore Wind Development in Nigerian Shallow Water Locations

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ABSTRACT

This study evaluates the viability of WindPACT-1.5 MW Horizontal Axis Wind Turbine (HAWT) for offshore wind development in the shallow waters of Nigeria. With the imperative need to address escalating energy consumption and mitigate climate change impacts, offshore wind power holds promise, offering opportunities for substantial electricity generation and economic growth. In this study, key metrics were examined for three potential offshore electricity projects: Asabo, Forcados, and Bonny Offshores. Asabo Offshore demonstrated superior potential, projecting the highest electricity generation at 21,167,296.08 kWh, resulting in substantial revenue of ₦1,319,357,564.67 per annum. Moreover, its Levelized Cost of Electricity (LCOE) of ₦60.8184/kWh underscores its cost efficiency compared to Forcados and Bonny Offshore projects. Net profit analysis further revealed Asabo's positive financial returns, is very low and there are net losses for the other two sites. Notably, Asabo Offshore showcased a 2.49% Return on Investment (ROI), indicative of a very low profitability, while Forcados and Bonny Offshore indicated negative ROIs of -46.74% and -48.39%, signaling potential financial setbacks. This comprehensive evaluation demonstrates that the WindPACT-1.5 MW HAWT, does not hold significant promise for offshore wind development in Nigeria's shallow waters.

1. INTRODUCTION

The escalation in energy consumption parallels the swift advancement of society and the economy. At the same time, climate change stands as an inevitable fact, demanding efforts to alleviate its consequences (Juan, et al., 2022). Consequently, directing resources towards sustainable energy sources offers the dual benefit of diminishing pollution and harnessing limitless reserves from clean energy sources such as the ocean waves, offshore wind, or the tides. Wind power has garnered increasing attention due to its inherent benefits: its abundance, renewable nature, inherent cleanliness, cost-effectiveness, and minimal adverse environmental effects. As a result, wind energy is being embraced as a substitute for fossil fuels, serving as a crucial strategy for sustainable global resource and environmental development (Ogulata, 2003, & Eskin et al., 2008). Additionally, wind energy assumes a pivotal role in propelling national economic growth, thereby generating enhanced employment opportunities (Philippopoulos et al., 2012, & Wais, 2017).

Various studies have been made on the viability of offshore wind turbines as evidenced in the work of Keivanpour et al. (2017), in which a systematic review was

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performed analyzing studies addressing global offshore wind energy potential published between 2000 and 2016. The authors highlighted key assessment criteria and relevant tools/methods. Effiom et al (2016) assessed offshore wind farm feasibility in Nigeria, focusing on a 500 MW OWT project. Their model analyzed costs across phases, revealing >50% of expenses from CAPEX and <50% from OPEX. Results showed a 4.95% LCOE reduction for 4 MW power and 2.7% reduction for 5-6 MW. Cost stability was noted at 300-500 MW, with decreasing LCOE in all phases and slight CMS detectability drop. This hinted at Nigeria's OWT potential, particularly for preliminary research.

Pires et al. (2017) conducted a systematic literature review on economic feasibility studies of offshore wind energy. Their work showcased the increasing interest in offshore wind power generation and its economic feasibility assessment. The study outlined key trends in the field such as wind farm analysis, risk assessment, floating offshore wind farms, decommissioning and repowering strategies, net present value analysis, life cycle cost assessment, and multi-criteria decision-making. This comprehensive overview provided insights for investors and researchers while proposing a research agenda. Liu et al. (2021) conducted a systematic literature review on methodologies used in offshore wind power investment decision-making. The authors categorized selected papers based on publication year, journals, author affiliations, method considerations, and application fields, revealing improved popularity and applicability of these methods post-2015. The study suggested a parallel or complementary implementation of different methods, aiding decision-makers in choosing the best-suited approach for investment viability.

Lo et al. (2021) introduced an assessment framework for optimal alternative selection in the face of conflicting criteria. Their hybrid model combined the grey decision-making trial-and-evaluation laboratory-based analytic network process (grey DANP) and probability-based grey relational analysis (P-GRA) methods. The model improved the effectiveness of traditional DANP and GRA methods, contributing to solving site selection challenges for sustainable development. Bosch et al. (2018) proposed a Geospatial Information System methodology to estimate global offshore wind energy potential by considering capacity factors of wind farms based on high-resolution wind speed data. This methodology provided insights for economically viable offshore wind energy potential assessment on a global or per-country basis.

Kumar et al. (2021) assessed the wind resource potential along the west coast of Gujarat for offshore wind farms. They highlighted the feasibility of 500 MW to 2 GW rated power wind farms with high-capacity factors. The study revealed potential for cost-effective installations on floating support structures, with floating installations offering lower LCOE for most locations. Sim (2023) utilized the Geske compound option model within a system dynamics framework to evaluate potential offshore wind farm sites in South Korea. The study emphasized flexibility and uncertainty in the site evaluation process while estimating the environmental benefits in terms of carbon emission reduction.

It becomes imperative to evaluate the potential of wind energy in Nigerian shallow water offshore locations using WindPACT-1.5MW Horizontal Axis Wind Turbine

in order to analyse the feasibility and economic viability of the development of offshore wind turbine projects in such locations. Hence, this study aims at analyzing the feasibility of WindPACT HAWT application in three shallow water locations in Nigeria.

1.1. Overview of the WindPACT-1.5MW Horizontal Axis Wind Turbine

The widely used wind turbine design is the horizontal axis with a propeller rotor. As stated by Rus (2020), these turbines demonstrate a high-power coefficient, typically ranging from 0.35 to 0.45. In this specific research, a conservative value of 0.35 was adopted for power output calculations, representing the worst-case scenario. The WindPACT-1.5 MW upwind HAWT was chosen as the wind turbine model for this study, featuring a three-blade design with each blade measuring 34.125 meters in length and a rotor diameter of 70 meters. These turbines utilize three horizontal axis fiberglass blades, and their hub is connected to a main shaft comprising multiple stages of gears to amplify rotational speed and transfer captured wind energy to a dual feed electric machine for conversion into electrical energy. The pitch electric and yaw systems control the blade angle and turbine direction. The maximum generator output for this type of wind turbine is 1.5 MW. As mentioned by Oday et al. (2019), the nacelle, which houses the alternator and gearbox, is strategically positioned at a considerable height to minimize noise emissions.

The WindPACT-1.5 MW HAWT employed in this study have a rotor Diameter of 70m, hub diameter of 3.50m, tower base diameter of 5.6 m, hub height of 84m, hub overhang of 3.3 m, the rotor orientation and configuration is upwind with three blades, the control is that of a variable speed with collective pitch, the rated tip and generator speed is 75 m/s and 1,800 rpm respectively, its shaft tilt & cone angles are 5°and 0° respectively, it has a rotor mass of 32,167kg, a nacelle mass of 52,839kg, tower mass of 125,364kg and a Cut-in speed of 3m s^{-1} (Rinker & Dykes, 2018, Clifton et al., 2013).

2. METHODOLOGY

Data regarding wind conditions were gathered from three shallow water offshore locations in Nigeria, specifically the Asabo, Forcados, and Bonny sites. Specialized instruments and parameters were employed to collect this information. For the Asabo location, the wind data was collected from April 7, 1981, to September 1, 1983, at coordinates 4.1166 latitude and 7.8 longitude. The water depth at this site is approximately 43 meters. The Continuous Observation of Embedded Multicore Systems (COEMS) instrument was utilized to obtain the data. The measurements were taken at a sample duration of 1 second, with recordings recorded at 60-second intervals. The sensor height initially set at 30 meters was later adjusted to 10 meters above mean sea level. At the Nigeria Forcados platform E-block, situated at coordinates 5.3605 latitude and 5.349 longitude, the wind speed and direction were measured using the S2000 mechanical met station, which was deployed by Hunting Surveys Limited on January 3, 1980, and operated until September 1982. The continuous chart recordings method was employed, with a sample duration and recording interval both set at 60 seconds. The sensor height was 6.5 meters but was corrected to 10 meters above mean sea level. For the Bonny site, wind data was collected between June 6, 1979, and October 4, 1982, at Nigeria Bonny platform site 1 (K-block), located at coordinates 4.4036 latitude and 7.1366 longitude. The S2000 Mechanical Met Station was used as the instrument for data collection. The sample duration and recording interval were both set at 60 seconds, and the sensor height was positioned at 10 meters above mean sea level.

Fig. 1: Monthly mean wind speed at Nigerian Shallow Water platforms

The wind data collected at three shallow water offshore locations in Nigeria, namely Asabo, Forcados, and Bonny, varies across the months. In general, the wind speeds are relatively higher at the Asabo location compared to the other two sites, reaching a peak of 7.1 m/s in August. Forcados consistently records the lowest wind speeds throughout the year, with the lowest monthly mean of 1.2 m/s in January. Bonny exhibits moderate wind speeds, with some fluctuations, and records the highest mean wind speed of 5.4 m/s in July. The wind patterns at these locations display seasonal variations, with higher speeds observed in the middle months of the year (June to August) and relatively lower speeds in the beginning and end of the year.

The potential power output of the horizontal-axis offshore wind turbine (HAWT) can be determined based on aerodynamic principles and the turbine's performance characteristics. Typically, the power output is computed using Equation 1:

$$P = 0.5 \times \rho \times A \times C_p \times V^3 \quad (1)$$

Where: P = Wind turbine's power output
ρ = Air density (kg/m^3),
A = The rotor's swept area (m^2),
Cp = Power coefficient
V = Wind speed (m/s).

The power coefficient (Cp) is a unitless parameter that relies on the wind turbine's design and characteristics.

The swept area of the rotor can be determined utilizing the Equation 2:

$$A = \pi \times R^2 \quad (2)$$

where R = Radius of the rotor.

The levelized cost of electricity (LCOE) and return on investment (ROI) was employed in order to assess the financial viability of Windpact-1.5 MW HAWTs in the considered locations. The LCOE represents the average cost of generating electricity over the lifetime of the wind turbines, including installation, operation, maintenance, and decommissioning costs. It is calculated by dividing the total lifetime costs by the total electricity generation.

LCOE = (Total Lifetime Costs / Total Electricity Generation, kWh) (3)

Return on Investment (ROI) is a measure of the profitability of the investment in Windpact-1.5 MW HAWTs. It represents the ratio of the net profit to the initial investment, expressed as a percentage.

ROI = ((Total Revenue - Total Costs) / Initial Investment) * 100 (4)

3. Results and Discussion

3.1. Data Analysis

To assess the monthly power output of the wind turbine at the Asabo, Forcados, and Bonny shallow water locations, their respective wind data was utilized for calculations. The outcomes of these computations are displayed in Figure 2. The WindPACT HAWT chosen for this analysis has a cut-in speed of 3 m/s, which represents the minimum wind speed required for the turbine to initiate electricity generation. This cut-in speed aligns with the usual range of 3–4 m/s observed in most turbines (Cole, 2023).

Table 1 shows the results of the calculated techno-economic analysis of the application of the windPACT-1.5 MW turbine for 20 years lifetime.

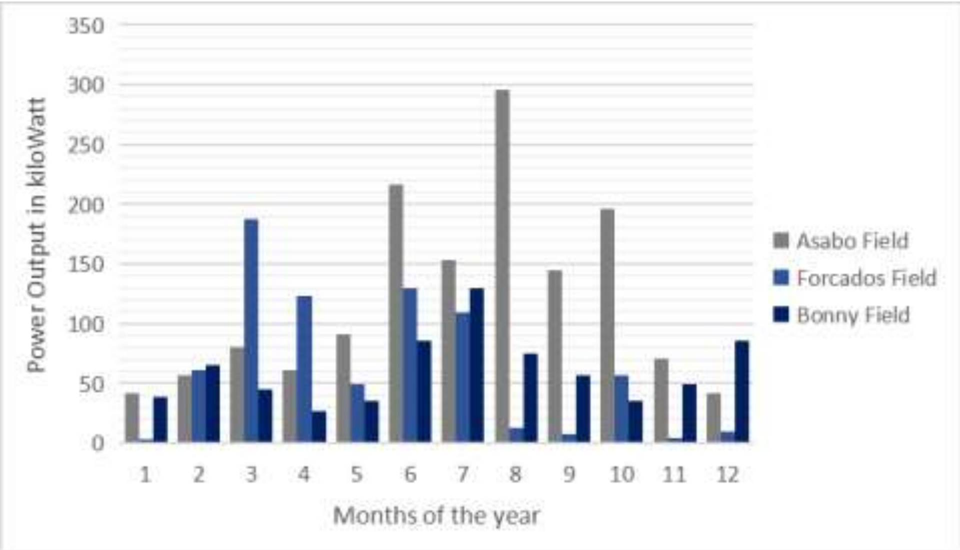

Fig. 2: Potential Monthly Power Output

Table 1: Tecno-Economic Analysis for Asabo, Forcado and Bonny Offshore Sites

Parameters	Asabo Offshore	Forcado Offshore	Bonny Offshore
Total annual electricity generated	21167296.08kWh	11000632.8 kWh	10659816.24 kWh
Total revenue	₦1319357564.67	₦685,669,442.42	₦664426346.239
LCOE	60.8184 ₦/kWh	₦ 117.026/ kWh	₦120.7677 / kWh
Net profit	₦ 31995764.67	-₦ 601692357.57	-₦ 622935453.76
ROI	2.49 %	-46.74 %	-48.39%

The parameters in Table 1 offers insights into their potentiality of Asabo, Forcados, and Bonny Offshore locations in terms of electricity generation, financial performance, and overall viability. Asabo Offshore has the potential of generating the highest a8mount of electricity at 21,167,296.08 kWh, followed by Forcados Offshore with 11,000,632.8 kWh, and Bonny Offshore generating 10,659,816.24 kWh. This indicates that Asabo Offshore has the highest capacity for electricity generation among the three. In terms of revenue, Asabo Offshore has the potential of generating the most revenue at ₦1,319,357,564.67, followed by Forcados

Offshore at ₦685,669,442.42, and Bonny Offshore at ₦664,426,346.239. This suggests that Asabo Offshore has the potential of not only generating the most electricity but can also turn it into higher revenue compared to the others.

The Levelized Cost of Electricity (LCOE) provides insight into the cost efficiency of these projects. The data indicates that Asabo Offshore will have the lowest LCOE at ₦60.8184/kWh, while Forcados Offshore's LCOE will stand at ₦117.026/kWh, and Bonny Offshore's at ₦120.7677/kWh. This indicates that Asabo Offshore will have a more cost-effective approach to electricity generation compared to the other two locations. Net profit reveals the financial performance after deducting all costs. Asabo Offshore is capable of generating a net profit of ₦31,995,764.67, indicating positive financial returns. In contrast, Forcados Offshore will face a net loss of -₦601,692,357.57, and Bonny Offshore will also experience a net loss of -₦622,935,453.76. This implies that Asabo Offshore is the only project among the three that is capable of generating a positive net profit, despite being low.

Return on Investment (ROI) is a critical metric for assessing the profitability of an investment. Based on the analysis, Asabo Offshore is capable of achieving a 2.49% ROI, suggesting that it will generate a positive return, despite being too low. On the other hand, Forcados Offshore and Bonny Offshore recorded negative ROIs of -46.74% and -48.39% respectively, indicating that investment in these projects will result in significant financial loss.

4. CONCLUSION

The potential of the WindPACT-1.5 MW Horizontal Axis Wind Turbine (HAWT) for offshore wind development in Nigeria's shallow waters has been studied. Wind data specific to each location were collected and utilized to calculate the potential power output for these three sites. The techno-economic analysis of these sites was conducted. The outcomes of the data scrutiny reveal the Asabo Offshore project as the most promising endeavor, despite displaying underwhelming performance metrics in critical aspects including electricity generation, revenue generation, Levelized Cost of Electricity (LCOE), net profit, and Return on Investment (ROI). In contrast, the Forcado Offshore and Bonny Offshore projects are anticipated to encounter profitability challenges, with negative net profits and ROIs indicating substantial financial obstacles. This study concludes that the potential of the WindPACT-1.5 MW HAWT for offshore wind development in Nigeria's shallow waters is limited. The outcomes of this research not only provide valuable insights for practitioners but also establish a foundational reference for researchers interested in advancing the field of offshore wind energy generation.

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Appendix A. Monthly mean wind speed at Nigerian Shallow Water platform

Table A1: Monthly mean wind speed at Nigerian Shallow Water platform

Month	Asabo Offshore	Forcados Offshore	Bonny Offshore
January	3.7	1.2	3.6
February	4.1	4.2	4.3
March	4.6	6.1	3.8
April	4.2	5.3	3.2
May	4.8	3.9	3.5
June	6.4	5.4	4.7
July	5.7	5.1	5.4
August	7.1	2.5	4.5
September	5.6	2.1	4.1
October	6.2	4.1	3.5
November	4.4	1.8	3.9
December	3.7	2.3	4.7

Appendix B. Monthly Mean Power Output of WindPACT-1.5 MW HAWT in kW

Table A2: Monthly Mean Power Output of WindPACT-1.5 MW HAWT in kW

Month	Asabo Offshore	Forcados Offshore	Bonny Offshore
January	41.8061	1.4261	38.5072
February	56.8835	61.1481	65.6206
March	80.3357	187.3373	45.2883
April	61.1481	122.8747	27.0449
May	91.2764	48.9586	35.3866
June	216.3589	129.9619	85.6897
July	152.8479	109.4827	129.9619
August	295.3996	12.8960	75.2094
September	144.9436	7.6435	56.8835
October	196.7025	56.8835	35.8835
November	70.3061	4.8134	48.9586
December	41.8061	10.0420	85.6897

Appendix C. Economic Analytical Data

This section shows details of the data used for the economic analysis

According to Blewett (2021), the Cost of Wind Turbine is $1,300,000 USD per megawatt (₦599,846,000.00). This implies that, a 1.5 megawatt wind turbine will cost $1,950,000 USD (₦899,769,000.00). Based on research on wind turbine operational cost, the annual expenses for operation and maintenance amount to $42,000-$48,000 Blewett (2021). This study assumes that the operation and maintenance costs are effectively managed, hence the minimum value from the range will be utilized for this analysis. This implies that it will cost $840,000 (₦387,592,800.00) for Operation and maintenance for 20 years. The total life time cost is approximately $2790000 USD (₦1,287,361,800.00). The electricity tariff in Nigeria is ₦62.33/kWh as at 2020 (BBC, 2020).