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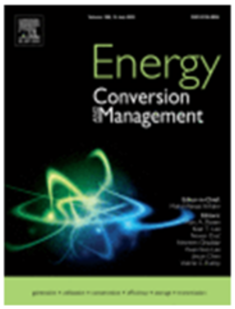

Techno-economic assessment of offshore wind energy potential at selected sites in the Gulf of Guinea

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Highlights

- Offshore wind potential in the coastline of Nigeria was assessed.
- Temporal/spatial analyses were conducted for the highest offshore wind potential.
- Wind characteristics and energy production of offshore turbines were evaluated.
- Among the selected sites, the best offshore site for wind exploitation was Agbami.
- Vestas V236-15.0 MW has the best performance among the selected turbines.

Abstract

Offshore wind power has been found to stand out among the most dynamic renewable energy technologies. With its long coastal line, Nigeria has an overwhelming advantage in developing marine energy resources to relieve the power crisis effectively. This work analyzed and characterized observation data of sea-surface wind speed and direction at 30-minute intervals between 1979 and 2015 at five synoptic offshore stations in the Gulf of Guinea. The seasonal variations in hourly surface wind speed and directions as well as the Weibull distribution of wind speed and wind power at 100 m hub height were examined. The wind shears, capacity factors, and accumulated energy outputs for seven offshore wind turbine types were determined for the selected locations. In addition, the economic analysis of the selected offshore turbines using levelized cost of energy was carried out, while sensitivity analysis of the total levelized cost of energy to key input parameters was further determined. The results revealed large spatial and temporal variations in wind speed and wind power in the Gulf of Guinea. The most viable offshore site for wind energy exploitation was Agbami (the deepest offshore site), while Bonny (the shallow coastal site) had the least. The findings established very good fits (having mean bias (between −0.08 ms^{-1} and −2.44 ms^{-1}), percentage bias (between −0.47% and −13.98%), correlation coefficients (between 0.97 and 0.98), Chi-square (between 0.2 and 1.2), and root mean square error (between 1.2 ms^{-1} and 3.1 ms^{-1})) between Weibull distribution and the actual wind data. The wind turbines with the highest and the lowest wind power densities, capacity factors, and power outputs across the seasons and sites were V236-15.0 MW and Siemens SWT113, respectively. The levelized cost of energy was considered for the deep waters due to the moderately high-capacity factors. The highest values ranged between 101.48 and 137.12 USD/MWh at Sea Eagle with V236-15 MW and V117-4.2 MW, respectively, while the lowest ranged from 52.29 to 69.66 USD/MWh at Agbami with V236-15 MW and Siemens (SWT113), respectively. The exploitation of Nigeria’s offshore wind resources could also be dedicated to producing renewable hydrogen and can serve to meet the country’s ambitious targets set for carbon neutrality by 2060.

Introduction

A transition to nature-friendly solutions for energy supply is very essential for the world in its quest toward carbon neutrality by 2060. To reduce greenhouse gases (GHG), adopting renewables will be of immense assistance [1]. Wind power is a promising and fast-emerging renewable energy resource for power generation. It is the most advanced among renewable sources, with the highest technological readiness level [1]. It has shown great potential in mitigating climate change and stimulating the global economy while boosting energy security [2]. Nigeria’s Energy Transition Plan (ETP) unveiled in 2021 sets out a timeline and framework for the attainment of emissions reduction; within the scope of the ETP, about 65% of Nigeria’s emissions are affected [3]. This ambitious target of ETP set to meet carbon neutrality by 2060, can easily be achieved by fully exploiting the country’s vast offshore wind and marine energy resources.

Several wind power projects have been completed in Africa, while some are ongoing. However, wind power development in Africa is currently confined to onshore development due to inadequate knowledge of offshore wind potential across the continent [4]. Despite a long shoreline and the vast deposit of offshore wind resources, Africa is yet to exploit its offshore wind power. Offshore wind technology is rapidly growing worldwide, with an additional 21 GW installed globally in 2021, which makes it more than triple the capacity deployed in 2020 [5]. The total global offshore wind installed capacity as of 2021 rose to 50,623 MW from 257 operating projects [6]. This remarkable growth in offshore wind development is largely attributed to China, followed by the United Kingdom, Denmark, and the Netherlands in Europe and the rest of the world (Vietnam, Taiwan). The annual growth rate of the offshore wind turbine is shown in Fig. 1. Despite the slow growth of offshore wind development when compared to onshore wind exploitation, offshore wind power still stood out among the most dynamic renewable energy technologies, based on installed capacity since 2010 [7], alongside its rapid technology developments, which showed potential for easier reduction of cost and the setting up of wind turbines in deep waters with the use of floating platforms [8]. Offshore wind power has also been found to trigger many benefits, such as job creation [9], enhancement of national energy security [10], global warming mitigation [11], [12], etc. Inappropriate assessment of offshore wind resources, environmental impact assessment and transmission infrastructure [13], identification of appropriate turbine foundation technology, logistics, installation, operational stability, grid connectivity, and security [14] were found to be the major challenges hindering offshore wind power developments.

Nigeria ranks among the countries with very low per-capita power consumption globally, as opposed to around 15,000 kWh in developed nations [8]. In line with Nigeria’s Nationally Determined Contributions (NDC), the country has shown keen interest in diversifying its energy mix by including renewable energy technologies (especially wind technology). This is done to accomplish a cumulative installed electric power capacity of about 20 % from renewables by 2030 (3.2 GW from wind, an additional 12 GW from large hydro, 3.5 GW from small hydro, and 6.5 GW of Solar PV) [15].

Wind energy resource has been highly underexploited in Nigeria; the only known is the installed 10 MW onshore wind farm in Katsina State, Nigeria. A number of studies have been conducted in assessing various onshore sites’ potentials across the country; for instance, wind energy potential for small communities in South-South, Nigeria [16], wind potential over selected coastal cities in Nigeria [17], wind energy potential in selected sites from three geopolitical zones in Nigeria [18], economic analysis of wind energy conversion systems in Nigeria [19], wind energy potential and the economics of wind power generation in Jos, Plateau State, Nigeria [20], wind resources in North-East geopolitical zone, Nigeria [21], wind energy resources for electricity generation in North-Central region, Nigeria [22], wind energy evaluation for electricity generation in seven selected locations in Nigeria [23], wind resource evaluation in six selected high-altitude locations in Nigeria [24], performance evaluation of wind turbines for energy generation in Niger Delta, Nigeria [25], and techno-economic evaluation of wind energy in South-West Nigeria [26]. However, for the offshore resource potential of Nigeria, very limited studies have been conducted to date, as given in Olaofe [27], [28].

Recent studies have shown a significant reduction in offshore wind energy's levelized cost of energy (LCOE) and found it to be highly attributed to the reduced cost associated with technological innovation [29]. With about 800 km of coastal line, Nigeria has an overwhelming advantage in developing marine energy resources. Hence, research on marine energy resources in Nigeria, such as offshore wind energy exploitation and other marine renewable energy conversion systems, must be conducted. In Olaofe [27], an assessment of the offshore wind speed distributions at 10 m height was carried out over the South-West coast of Nigeria using a 6-hourly

(00:00, 06:00, 12:00, and 18:00 UTC) Cross Calibrated Multi-Platform (CCMP) L3.0 over 10-years (2002–2011). In addition, the author (Olaofe [27]) further extended the work to consider an evaluation of the offshore wind resource over the coast of Africa [28], using CCMP L3.0 surface wind at 10 m height from 2001 to 2011. These works by Olaofe [27], [28] were found to utilize 10-year generated satellite wind speed datasets to provide an overview only of the offshore wind energy resource distributions across the coasts of Nigeria (in the South-West) and Africa, respectively.

Despite the technological advancement in wind energy exploitations, comprehensive study regarding the assessment of wind potential is critical and essential in the earlier stages of the wind power project [30], alongside the variability of power [31], seasonality [32], the trend in wind power [33], economic aspects [34], and the effects on local climate [35]. In Ichenial et al. [36], the stability state or condition of the atmosphere modifies the wind shear coefficient and energy generation from standard wind turbines. Hence, wind shear must be described most accurately because it is a major cause of cyclic loads of wind turbines [37]. In the coastal region, factors affecting wind speeds besides topography include the coastline orientation, water depth, air-sea temperature differences, prevailing wind speed and direction, latitude (related to the magnitude of solar radiative forcing), distance from the coastal discontinuity, and fetch (i.e., the surface type over which the wind blows) [37]. These physical processes and determinants are important to carry out an extensive estimation of wind resources for wind energy applications. The variability of wind power is determined by wind behaviour at different timeframes, thus calling for special consideration of this perspective. The feasibility of a wind power project is greatly dependent on the inherent temporal characteristics of the wind, hence the need to quantify the temporal variability of the resource through variability indices at different timescales [38], resource versatility, and persistence [39]. The wind fluctuates in nature, resulting in an inconsistent power supply by a degree that is highly related to the location. Spatial comparisons of variability metrics will provide insight into the locations where wind energy is less intermittent and more dependable.

An in-depth analysis using reliable/sea-surface measured offshore wind data (found to be better and much more reliable than generated/satellite data) is thus essential to convert offshore wind potential into a real offshore wind farm. Hence, the aim of this present study is to conduct a comprehensive techno-economic assessment of offshore wind potential in the Southern Atlantic Ocean bordering the coastline of Nigeria (also known as the Gulf of Guinea, GoG), using long-term offshore observation (sea-surface measured) data captured at five offshore synoptic stations in the GoG (see description of the dataset in section 2.1). In this work, the (i) spatio-temporal analysis of sea-surface wind observations at five offshore synoptic stations in the GoG, (ii) seasonal variations in wind speed and directions, (iii) evaluation of wind shear, wind power, capacity factor, and accumulated energy outputs at seasonal and annual time scales for the selected commercial offshore wind turbines, and (iv) economic analyses of offshore wind power development using LCOE, were conducted.

Section snippets

Material and methods

In assessing offshore wind resources along the GoG, the following aspects are of particular importance. In this section, the wind speed data and selection of sites, and the mathematical models adopted for this work, were comprehensively discussed.

Results and discussion

This section presents the technical and economic assessments of the offshore wind at the GoG.

Conclusions

This present study assessed offshore wind potential in the Gulf of Guinea. Analyses of temporal and spatial wind data were carried out to discover the offshore observation station with the highest potential for wind energy exploitation. The following were concluded:

- 1.
  There were large spatio-temporal variations in wind speed over the selected offshore sites in the GoG. The results revealed that the wind speeds increased from the shallowest (coastal location of Bonny) to the deepest offshore site

Suggestions for further study

The following are suggested for future work:

- 1.
  More input/empirical data sources on detailed system cost breakdown (such as lease price, plant commissioning, decommissioning, contingency, construction finance, insurance during construction, development, engineering management, port and staging, logistics, transportation for the fixed-bed and floating offshore plant), including industry collaboration, should be utilized to improve the accuracy of estimated LCOE in this region.
- 2.
  Studies should

CRediT authorship contribution statement

Olayinka S. Ohunakin: Conceptualization, Supervision, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Olaniran J. Matthew:** Validation, Writing – review & editing. **Muyiwa S. Adaramola:** Data curation, Writing – review & editing. **Opemipo E. Atiba:** Data curation, Writing – review & editing. **Damola S.**

Adelekan: Data curation, Writing – review & editing. **Oluwadamilare O. Aluko:** Writing – review & editing. **Emerald U. Henry:** Data curation, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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  The LCOE quantifies the cost of electricity production over the lifetime of any energy project [23]. Indeed, there already exist various LCOE-based studies for both bottom-fixed offshore wind [24–27] and FOWTs [15,27–30]. These studies have shown that the cost of energy for offshore wind has experienced a great reduction in recent years, although it is still far from conventional renewable energy sources, such as solar, biomass and onshore wind.
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