

Techno-economic and environmental assessment of battery integrated wind farm siting across offshore Nigeria

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Abstract

This study investigates the economic, technical, and environmental impacts of integrating a battery energy storage system (BESS) with an offshore wind farm near Koko Sea Port, Nigeria. As renewable energy curtailment increases and Nigeria's energy demand grows, energy storage systems (ESS) are essential for ensuring a firm power supply. While offshore wind farms have advanced globally, Nigeria remains underrepresented in related research. This study addresses this gap by presenting a comprehensive techno-economic and environmental assessment (TEEA) of an ESS-integrated wind farm along Nigeria's coast. The system includes 477 Siemens Gamesa SG 2.1-114 turbines, producing 930 GWh annually with an instantaneous output of 0.35 GW. Vanadium Redox Flow Batteries (VRFB) were identified as the most suitable ESS, providing 528 MWh of storage to maintain power during wind variability. Economic analysis indicates a Levelised Cost of Energy (LCOE) of 393.35 \$/MWh, comparable to global 2020 benchmarks for newly commissioned offshore wind farms. Environmental analysis reveals significant carbon savings, with emissions reduced by over 107% and 74% relative to coal and gas power plants. This study highlights the potential of battery-integrated offshore wind farms to advance Nigeria's clean energy transition, offering insights for policymakers and stakeholders pursuing sustainable development and Paris Agreement commitments.

Keywords: Offshore wind farm, energy storage system, vanadium redox flow battery, techno-economic and environmental assessment, multiple-criteria decision-making, carbon savings

Nomenclature

AEP	Annual Energy Produced
BEES	Battery Energy Storage System
BoP	Balance of Point
c2g	Cradle to Grave
CAPEX	Capital Expenditure
CF	Capacity Factor
Co ₂ eq	Carbon Emission Equivalent
CP	Capacity Performance
DSS	Distribution Substation
EC	Exporting Cables
EIA	Environmental Impact Assessment
ESS	Energy Storage System
GHG	Green House Gases
GHG	Green House Gas
GWP	Global Warming Potential
HES	Hydrogen Energy Storage
IAC	Inter Array Cable
IEC	International Electrotechnical Commission
LCOE	Levelised Cost of Energy
LCOS	Levelised Cost of Storage
Li-ion	Lithium Ion
MCDM	Multiple Criteria Decision-Making
NaS	Sodium Sulphur
OFL1	Offshore Location 1
OFSS	Offshore Substation
OFSS	Offshore Substation
OFW	Offshore Wind
OFWF	Offshore Wind Farm
OFWF + BEES	Battery Energy System Storage Integrated Offshore Wind Farm
ONSS	Onshore Substation
OPEX	Operation Expenditure
PA	Paris Agreement
PbO ₂	Lead Acid
PHES	Pumped Hydrogen Energy Storage
PHES	Pumped Hydro Energy Storage
PHES	Pumped Hydro Energy Storage
PHESL1	Pumped Hydro Energy Storage Location 1
RE	Renewable Energy
RES	Renewable Energy Sources
RET	Renewable Energy Technologies
RFB	Redox Flow Batteries
RNA	Rotor Nacelle Assembly
SDGs	Sustainable Development Goals
TEEA	Techno-Economic and Environmental Assessment
TES	Thermal Energy Storage

TOPSIS	Technique for Order of Preference by Similarity Index
VRFB	Vanadium Redox Flow Battery
WTG	Wind Turbine Generator

Introduction

The impact of fossil fuels on the world has resulted in global efforts towards NetZero in about three to four decades. Carbon emissions from fossil fuels have been suggested to harm human health, environmental sustainability and economic growth. Ergo, initiatives like the Paris Agreement (PA) and the United Nations Sustainable Development Goals (SDGs) have been inaugurated to limit global temperature rise to 1.5 °C through energy transition policies and plans (Cruz et al., 2024; Dannheim et al., 2020; Jung & Schindler, 2020; Malaekhe et al., 2022; Neupane et al., 2022; Paraschiv et al., 2022; Patidar et al., 2022; Vallejo-Díaz et al., 2022; Virtanen et al., 2022; Wang et al., 2024). Renewable Energy integration, amongst other initiatives, has been promoted and enforced by global north nations. However, these efforts have been much slower amongst global South Nations (Energy Institute, 2023; IRENA, 2023a). Availability of resources, competitive prices, technological development, and the race to NetZero have increased interest, investment and installations of wind farms across the globe (Delina, 2022; Düzcan & Kara, 2021; Juan et al., 2022; Paraschiv et al., 2022; Wu et al., 2013).

Wind energy has been opined to be the most economical option among new sources of power generation (Torralba et al., 2017). According to a report by IRENA on newly commissioned utility-scale power projects, wind energy was suggested to cost 0.162 USD/kWh, about 43 % less than a hydropower system at 0.381 USD/kWh, the highest renewable energy technology (International Renewable Energy Agency, 2021). Offshore wind is in high demand to replace fossil fuels, which still contributes around 976 pounds of CO₂ per MWh. These technologies bring about opportunities for carbon savings and economic growth through job creation and a favourable environment for industrialisation across developing nations like Nigeria (Ben et al., 2021; IRENA, 2023b).

Analogous to global north nations, the energy transition across Nigeria has been relatively slow. Today, renewable electricity accounts for only 26.66 % of the annual production of 40 TWh. Amongst these, large hydro supplies a significant amount at 21.84, Solar PV at 4.07 %, small hydro at 0.70 %, and wind the least at 0.05 % (Climatescope, 2022; Eweka et al., 2022; IRENA, 2023a). Nevertheless, Nigeria has been opined to have abundant offshore wind resources (Akporhonor et al., 2023; Ben et al., 2021; Somoye, 2023). Irrespective of Nigeria's

abundant viable wind resources for power generation, today, over 20 million Nigerian homes are without electricity. Nigeria's electrification rate stands at 56.5 %. It has been suggested that only a third of the 15 GW installed capacity generates power at peak capacity. The Nigeria electricity sector has been characterised by epileptic power supply, insufficient capacity, and low Renewable Energy (RE) integration. Alongside the above, an increase in the employment rate of 5.75 %, a population growth rate of 2.6 % and over 0.1 billion tons of fossil fuels and industry emissions in Nigeria demands a diversification of the current energy profile (Attabo et al., 2023; Ben et al., 2021; Eweka et al., 2022; Olaofe, 2017; Ritchie et al., 2020; Statista, 2023b).

To facilitate the Global, African, and Nigerian wind energy development, a substantial amount of research on wind energy potential and Techno-economic feasibility, as shown in Table 1 has been carried out in Nigeria and much more in the world at large. These studies have made significant contributions to the growth, development, and application of wind energy as a substitute energy source towards the global energy transition and NetZero by 2050, as well as to energy security. However, there persists low interest and investment in the Nigeria Wind energy sector (Akporthonor et al., 2023)

Accessible, sustainable, cost-effective, and NetZero emissions are requirements for all new power projects in the world today (Ambrose & Kendall, 2016; Yi et al., 2022) Of which wind power possesses. Global wind capacity is on a rapid increase due to competitive prices and has been opined to double every four years (Bird et al., 2016; Paraschiv et al., 2022). Despite these exciting stats, Renewable Energy Sources (RES) like wind are plagued with the problem of intermittency (Raza et al., 2024; Zivar et al., 2020). The variability of these resources often leads to irregular power supply, usually serviced by fossil fuel ancillaries. This challenges clean energy integration, energy transition and global temperature limitation. (Cruz et al., 2024; Vallejo-Díaz et al., 2022). Therefore, global integration of Energy Storage Systems (ESS) to RE power plants is necessary to achieve NetZero by 2050.

Consequential to those mentioned above, numerous authors have investigated energy storage integration to renewable energy, amongst which Bamisile et al., (2020) investigated the economic viability of renewable energy integration using pumped hydro storage to forecast the energy needs as well as power capacity intending to improve Nigeria's electrification to 100 %. Results indicated the need for more Renewable energy installation power capacity of 36000 MW to satisfy a predicted 200 TWh demand by 2030. Gupta et al., (2020) developed a model

to estimate the techno-economic implications of storage-integrated wind and PV farms to provide firm power. Eight storage systems, including Li-ion, Pb-acid, flow battery, etc, were considered. The levelised cost was the lowest for PV integration with Li-ion at utility and residential sites and with pumped hydro energy storage in bulk-scale installation.

More specifically, wind energy storage integration has also been studied by authors; for example, Yi et al., (2022) constructed a wind energy storage system to improve the reliability of wind farms to provide ancillary service for frequency regulation. In a study to enhance offshore wind farm black start capabilities, Pagnani et al., (2023) concluded the need for battery integration into wind power plants to replace conventional fossil power plants exploited when black start is required. More so, according to the authors, despite advances in wind power exploitation technologies, comprehensive studies on techno-economic and environmental impact are mandatory for early-stage wind project development. (Cai & Bréon, 2021).

Regardless of the expansive research on wind energy storage integration across the world, limited knowledge exists concerning Nigeria; thus, this study conducted a comprehensive techno-economic and environmental assessment of an energy storage-integrated offshore wind farm in the coastal regions of Nigeria.

To carry out the study's aim, the following objectives were employed:

- Identify and evaluate suitable offshore locations for wind farm installation
- Determine the optimal capacity for the wind farm and select appropriate wind turbine technologies
- Design an appropriate energy storage system (ESS) for the offshore wind farm, including the selection of suitable storage technologies
- Perform an economic analysis of the integrated wind farm and energy storage system
- Assess the environmental impact of the proposed offshore wind farm and energy storage system

The paper provides information that would aid the exploitation and exploration of battery-integrated offshore wind farms across Nigeria and provide opportunities for further advances and investigations. The outcomes could potentially guide policymakers and stakeholders in implementing clean energy projects that align with Nigeria's commitments to global environmental goals and sustainable development.

Table 1 Nigeria Wind Studies Publication

	Study summary
(Abam & Ohunakin, 2018)	Assessed wind energy potential at six locations in Cross River State, Nigeria, for electricity generation, utilising small-scale wind energy conversion systems (WECS).
(Abdullahi & Kehinde, 2023)	Conducted a statistical analysis to identify the most fitting frequency distribution models (Weibull, Rayleigh, and Gamma distribution functions) for wind speed data across Jos, Kano, and Minna in Nigeria.
(Ajayi & Katende, 2011)	Analysed the wind characteristics specific to Shaki and Iseyin in Oyo State, Nigeria.
(Akporhonor & Otuagoma, 2023)	Evaluated the methods, periodicity, and time series of wind speed data collection for wind energy studies within Nigeria.
(Akporhonor et al., 2023)	Reviewed Nigeria's wind energy potential, energy capacity, and policies related to renewable energy.
(Attabo et al., 2023)	Assessed the economic feasibility of deploying wind turbines for electricity generation at selected coastal and offshore sites in Nigeria.
(Attah et al., 2021)	Performed a technical evaluation of offshore wind resources in the Gulf of Guinea, focusing on the Lagos region.
(Ayodele et al., 2016)	Investigated the potential for wind energy to generate electricity at 15 different sites across Nigeria's six geographical zones, providing data to inform optimal investment in wind technology.
(Ben et al., 2021)	Examined wind characteristics, variation patterns, and power potential across 13 cities in central and southern Nigeria, comparing the performance of various estimation methods, including graphical, empirical, and maximum likelihood techniques.
(Eboibi et al., 2017)	Explored wind energy potential in six locations within the South-South geopolitical zone of Nigeria (Asaba, Benin, Calabar, Port Harcourt, Uyo, and Warri) as potential sites for wind energy generation.
(Ohunakin, 2011)	Carried out a statistical analysis of wind characteristics at five locations (Bida, Minna, Makurdi, Ilorin, and Lokoja) in Nigeria using Weibull distribution functions.
(Ohunakin et al., 2023)	Characterised sea-surface wind speed and direction based on observation data collected at 30-minute intervals from 1979 to 2015 at five offshore stations in the Gulf of Guinea.
(Okeniyi et al., 2015)	Analysed 11 years of daily average wind-speed data recorded at Akure, Nigeria, applying Weibull and Rayleigh distribution functions.
(Onoruoiza et al., 2022)	Investigated wind speeds in Jos, Kano, Ilorin, Lagos, and Port Harcourt, Nigeria, utilising wind data obtained from the Nigeria Meteorological Agency
(Oyewole & Aro, 2018)	Evaluated wind power potential and economic feasibility for commercial energy production in Eket and Uyo, Nigeria.
(Udoakah & Ikafia, 2017)	Explored the wind energy potential in three offshore areas of Nigeria (Lagos VI, Rivers Abonemma, and Warri Koko) using Weibull, Rayleigh, and Exponential distribution models.

Methodology

Site Selection and Wind Farm Design Methodology

Wind Power is the second largest and most promising renewable energy technology. Wind has recently experienced rapid development due to competitive installation costs. Across the world, both new onshore and offshore capacity has been commissioned as global offshore wind (OFW) capacity augmented from about 19 GW in 2017 to 55 GW in 2022 (Dannheim et al., 2020; Gonen, 2012; Paraschiv et al., 2022; Shahabuddin et al., 2021; Wang et al., 2024).

Site Selection Criteria

The selection of a suitable site for the installation of an offshore wind farm is determined by several factors related to economics, policies, environmental implications, and social impacts. However, estimating location suitability using the availability of good wind energy potential, distance from shore and water depth must take pre-eminence (Onoruoiza et al., 2022). Three offshore locations, OFL1, OFL2 and OFL3, were considered due to proximity to Sapele transmission Substations and Koko Seaport to reduce transmission losses and installation and transportation costs. Site aggregate wind speed, distance from shore and water depth (as seen in Table 2) were retrieved as criteria to determine the most suitable locations.

Table 2 OFL Location Summary

	Latitude (°N)	Longitude (°W)	Mean Wind Speed at 10 m (m/s)	Distance From Shore (km)	Water Depth (m)
OFL1	5.25	4.89	3.95	40.6	82
OFL2	5.37	4.96	3.98	29.4	44
OFL3	5.17	4.84	3.92	56	219

Sources: (Global Wind Atlas, 2023)

Employing the Technique for Order of preference by similarity to ideal solutions (TOPSIS) and The Analytical Hierarchical Process (AHP), a multiple criteria decision-making (MCDM) was carried out as indicated below (Li et al., 2024).

Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)

TOPSIS can be evaluated in six steps (Chakraborty, 2022; Owebor et al., 2022; Rahim et al., 2018)

1. Decision matrix normalisation

Each criterion is divided by its norm in this stage to convert criteria to non-dimensional variables.

$$r_{ij} = \frac{x_{ij}}{\sqrt{x_{ij}^2}} \quad 1$$

2. Integrating normalised decision matrix

The normalised decision matrix and weight vectors are integrated using equation (2)

$$V_{ij} = w_i \times r_{ij} \quad 2$$

Where $i = 1, 2, \dots, m; j = 1, 2, \dots, n$

In this study, the weight vector was estimated using the Analytical Hierarchy Process (AHP) (Owebor et al., 2022).

3. Evaluation of positive and negative ideal solution

$$A^+ = [v_1^+, v_2^+, \dots, v_n^+] \quad 3$$

$$A^- = [v_1^-, v_2^-, \dots, v_n^-] \quad 4$$

Where,

$$v_j^+ = \begin{pmatrix} \max v_{ij}, \text{ if } j \text{ is a benefit attribute} \\ \min v_{ij}, \text{ if } j \text{ is a cost attribute} \end{pmatrix}$$

$$v_j^- = \begin{pmatrix} \min v_{ij}, \text{ if } j \text{ is a benefit attribute} \\ \max v_{ij}, \text{ if } j \text{ is a cost attribute} \end{pmatrix}$$

4. Calculating Euclidean distance

The distance between each alternative from the ideal negative and positive solution were estimated using equation (5).

$$S_i^+ = \sqrt{\sum_{j=1}^n (v_{ij} - v_i^+)^2} \quad 5$$

$$S_i^- = \sqrt{\sum_{j=1}^n (v_{ij} - v_i^-)^2} \quad 6$$

5. Relative closeness to the ideal solution

The closeness to the ideal solution of each alternative was determined using (7)

$$C_i^+ = \frac{S_i^-}{S_i^+ + S_i^-} \quad 7$$

6. Alternative ranking

Alternate rankings are based on the Highest Value of the relative closeness to the ideal solution. (Chakraborty, 2022)

Weight vector determination used in TOPSIS analysis

The weight vector used in the TOPSIS analysis was determined using The Analytical Hierarchical Process (AHP)

AHP is estimated in three steps.

1. Development of pairwise matrix using the Balanced scale equivalence chart as seen in Table 3 (Brunelli, 2015)
2. Estimating weight vector, w_i using equation (8)

$$w_i = \frac{(\prod_j^n a_{ij})^{\frac{1}{n}}}{\sum_i^n (\prod_j^n a_{ij})^{\frac{1}{n}}} \quad 8$$

3. Determination of the consistency ratio CR

$$CR = \frac{CI}{RI_n} \quad 9$$

4. Where CI is the Consistency Index

$$CI = \frac{\lambda - n}{n - 1} \quad 10$$

5. RI_n is Random Index values as obtained from (Abu Dabous & Alkass, 2008)

Table 3 Balanced Scale Equivalence of Verbal Description of Pair Wise Comparison

Verbal Description	Balance Scale
Indifference	1
	1.22
Moderate Preference	1.5
	1.86
Strong Preference	2.33
	3
Very Strong Preference	4
	5.67
Extreme Preference	9

Sources: (Brunelli, 2015)

TOPSIS ranking for site selection

TOPSIS rankings, as seen in Table 4 estimated Offshore Location 2 (OFL2) 5.37 °N and 4.96 °W, with a mean wind speed of 3.98 m/s at height 10 m as the most suitable site.

Table 4 OFL Location TOPSIS Ranking

	Similarity Index	TOPSIS Ranking
OFL1	0.55	2
OFL2	0.56	1
OFL3	0.5	3

Selected Site description

Figure 1 displays a pictorial representation of the wind resources available at the southern coastal line of Nigeria. Regions closer to the colour “red” indicate higher and colour “yellow” moderate wind speed. Selected site Offshore location 2, 5.37 °N and 4.96 °W, as indicated using a blue pointer in Figure 1 displays relative moderate wind speed suitable for wind farm installation (Akporhonor et al., 2023)

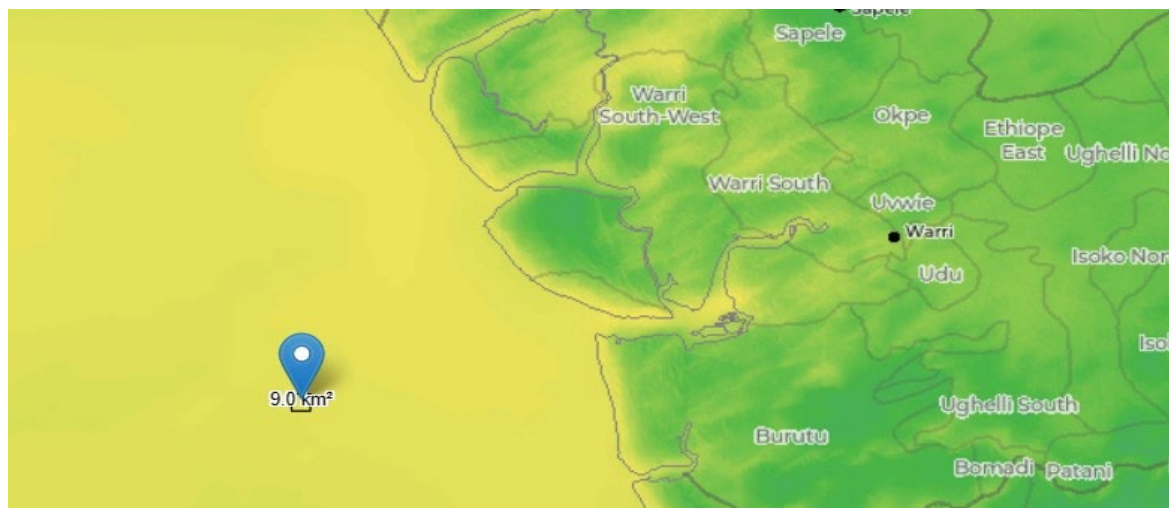


Figure 1 Map of the southern Coastline of Nigeria

Sources: (Global Wind Atlas, 2023, modified)

As represented in Figure 2 OFL 2 was estimated at 44 m water depth, 29.4 km across the south-south Nigeria coastline and 65.0 km from the Sapele Transmission substation, as displayed in (Adoghe et al., 2023).

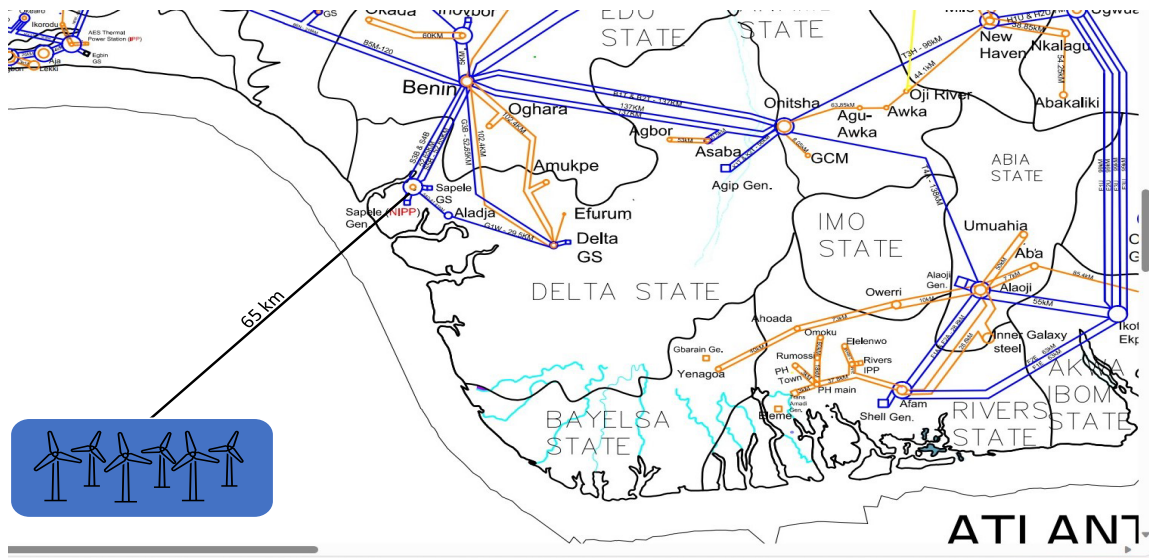


Figure 2 Graphical Representation of Propose Offshore Wind Farm

Sources: (Transmission Company of Nigeria, 2023)

Determination of Wind farm capacity

Wind power from different regions can be harnessed using electromechanical conversion systems called Wind Turbine Generators (WTG). Wind farms are commonly made up of several independent WTG and Balance of Point systems. (Mo et al., 2013). Figure 3 Illustrates a pictorial representation of key components of a wind farm.

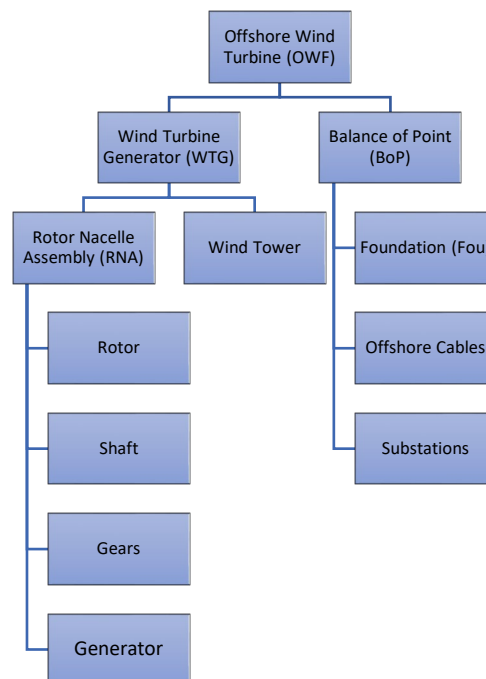


Figure 3 Components of an Offshore Wind Farm

Determining a suitable capacity for power plants hinges on several key factors, including economic feasibility and energy demand. Putting into consideration the Nigerian electricity profile characterised by insufficient supply, a poor electrification rate of 56.5 %, a rising energy demand rate of 7-13 % and a population growth rate of 2.6 % (Climatescope, 2022; Eweka et al., 2022) There will also be global conversations for all new offshore wind farms to be capped at a minimum of 1 GW to facilitate the “2000 GW installed offshore capacity by 2050 goal.” (Putuhena et al., 2023). A 1 GW offshore wind farm was proposed in this study to aid Nigeria's power generation of about 40 kWh carted to an energy demand of over 29 TWh. (Climatescope, 2022; Statista, 2023a).

Selection of Wind Turbine Technology

Wind turbine: A wind turbine generator (WTG) is the summation of all components required to capture wind resources and convert them into usable electrical energy. It comprises the tower and Rotor Nacelle Assembly (RNA). The adoption of WTG for any location is subject to available wind speed. The mean wind speed of the considered location must be greater than or equal to the turbine cut-in wind speed. Location wind speed also determines the International Electrotechnical Commission (IEC) classification of wind turbines. Putting into consideration the wind profile of OFL2, Siemens Gamesa (SG) 2.1-114 with a cut in wind speed of 3 m/s and rated power of 2.1 MW as illustrated in Table 5 was selected in this study. A wind farm capacity of 1 GW would require the installation of approximately 477 SG 2.1/114 turbines.

Table 5 Turbine Specifications

		Rated Power (KW)	Cut-in Wind Speed (m/s)	Rated wind Speed (m/s)	Cut-Out wind Speed (m/s)	Rotor Diameter (m)
SG 2.1-114 Turbine		2100	3.0	9.0	23.0	114

Sources: (Alham et al., 2023; Wind turbine Models, 2023)

Turbine tower: Wind turbine towers are made of steel or concrete materials. Towers are hollow structures that connect turbine foundations and RNA via a transition piece. Tower typical house cables, elevators, and ladders leading up to the nacelles determine the RNA's hub height (Cruz et al., 2024). According to the authors, wind energy potential increases with altitude; thus, when selecting a turbine tower, energy maximisation is a key focus (Alham et al., 2023). In this study, the mean wind speed OFL2 across four heights with an interval of 50

m was retrieved, as seen in Table 6, and the hub height with the highest average wind speed of 150 m at m/s was selected (Global Wind Atlas, 2023).

Table 6 Mean Wind Speed of OFL2 at Different Hub Heights

	Hub Height (m)	Mean Wind Speed (m/s)
OFL2	50	4.72
	100	5.15
	150	5.2
	200	5.19

Sources: (Global Wind Atlas, 2023)

Blades: Turbine blades directly interact with available wind speed across the location to cause rotor rotation (Cruz et al., 2024). WTGs often experience loss in performance due to downward wave turbulence called wakes. When siting a wind farm, it is more profitable to site turbines as close as possible. However, due to the wake effects of turbines, a 5R – 8R (five times rotor diameter, 8 times rotor diameter downwind) is the rule of thumb. (Al-Addous et al., 2020; Williamson et al., 2002). However, in this study, the 7D (seven times diameter) was used to maximise profit (Ashuri et al., 2016). Each turbine was given a separation distance of 11.4 km.

Rotor turbine assembly: Rotor Nacelle Assembly (RNA) refers to the nacelle and all its components. A nacelle houses electrical and mechanical components required for energy generation. These include gearbox, shaft, generator, etc. (Cruz et al., 2024). During operation, turbine blade rotation is translated from the blades to the wind generator through a shaft. The wind-to-speed ratio is increased by the gearbox connected to the generator to produce power. The SG 211-114 turbine has one generator with a maximum voltage of 690 V and a frequency of 50 Hz (Wind turbine Models, 2023).

Balance of plant: Power generated from wind farms is transmitted to an Offshore substation (OFSS) using inter-array cables (IAC), stepped up and further transmitted to onshore substations (ONSS) or, in some cases, directly to a utility grid using exporting cables (EC). Alongside the turbine foundation and Transition piece, OFSS, ONSS, IAC and EC comprise a turbine's Balance of Point (BoP).

Offshore wind energy estimation

The output power (P_o) of SG 2.1-144 wind turbine at OFL1 was estimated in (11) as a factor of bertz coefficient of power (C_p), which determines the percentage of available wind that a wind turbine can harness assumed at a maximum of 59.3 %, density of air at sea level (ρ) given as 1.225 kg/m^3 , retrieved wind speed at height 150 m (V) estimated as 5.2 m/s, and the area of air fluids that reaches the turbine is evaluated using (12) (Alham et al., 2023; Cakiroglu et al., 2024; Global Wind Atlas, 2023; Uddin & Sadiq, 2023).

$$P_o = \frac{1}{2} \times \rho \times A \times V^3 \times C_p \quad 11$$

$$A = \frac{\pi D^2}{4} \quad 12$$

Annual output energy for a single turbine at OFL2 was evaluated using 13

$$AEP = P_o \times CF \times 8760 \quad 13$$

CF is the ratio of generated energy and the maximum amount of energy that can be generated across a location (Teimourian et al., 2020). In this study CF was estimated using the wind atlas algorithm by inputting turbine specifications and assumed a loss of 10 %. results put CF at 0.30 (Davis et al., 2023; Global Wind Atlas, 2023). Table 7 displays the result of the output power and Annual output energy of the siting SG 2.1/144 turbine.

Table 7 Annual Output Energy and Power Output of Proposed Wind Farm

	Output Power (MW)	Annual Output Energy (MWh)
SG 2.1/144	0.743	1953.75
Wind Farm	354.018	930359.14

The maximum generation capacity of the SG 2.1/114 Turbine at OFL2 was approximately 0.74 MW, and annual energy generation was 1953.75 MWh. Cogitating the wind farm of approximately 477 Turbines and instantaneous power generation gave 354.2 MW and a yearly output of 620 GWh. Results showed a slight difference in actual and rated power output due to technical and environmental factors.

Energy storage system design

Accurately predicting future loads is essential to design a storage system. The 2021 Nigerian 29 TWh energy demand and 40 kWh energy supply illustrate that $< 2\%$ of the national load was met. (Climatescope, 2022; Gangopadhyay et al., 2024; Statista, 2023a). The over 28 TWh deficit in energy production establishes the need for all 930 GWh estimated to be produced by *OFWF Oriste*. Thus, this study assumed the proposed system's grid demand for all annual generated power.

However, the variability of wind resources results in other challenges like an uneven supply of wind power, which requires the service of ancillary systems mainly catered by fossil fuel-powered plants (Ren et al., 2017). Therefore, there exists a need for the integration of ESS to guarantee a firm power supply from *OFWF Oriste* to the Nigerian grid (Chen et al., 2020; Lee et al., 2023; Pourebrahim et al., 2021).

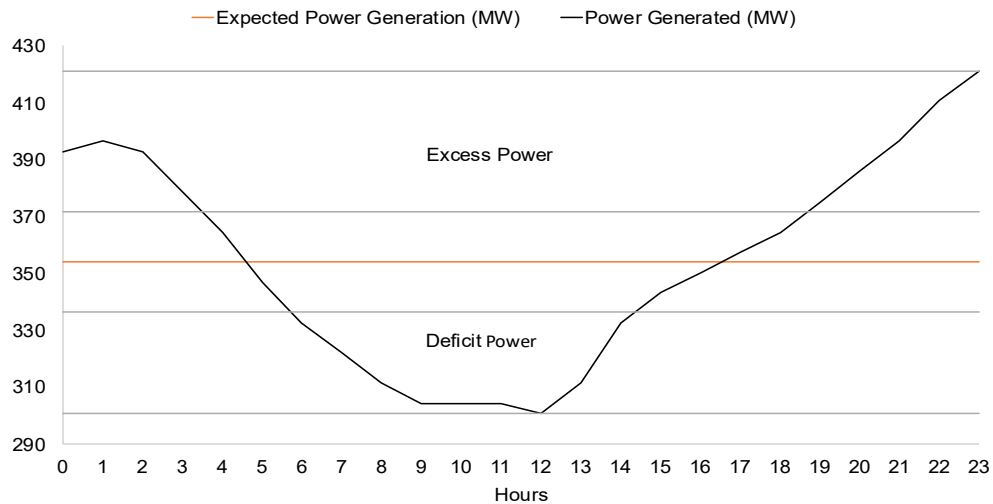


Figure 4 Graphical representation of *OFWF* output power and estimated hourly generated power.

Figure 4 illustrates a graphical representation of the expected output power (P_{OFWF}) and estimated actual hourly generated power of *OFWF*, developed by correlating hourly wind speed index retrieved at 100 m height on October 29th, 2023, from Global Wind Atlas, 2023 and P_{OFWF} . A close look at Figure 4 demonstrates power production excesses and deficits ranging from 10.62 - 67.26 MW and 3.54 - 49.56 MW respectively, across different hours of the day due to wind energy intermittency. The illustration expands on the fact that the proposed system cannot guarantee firm power and would require ancillary services. However, installing an energy storage system to capture excess power within the 0 – 5th and 17th – 20th hour of the

day and supply from the 5th – 17th hour would mitigate all frequency irregularities from variable energy supply, guaranteeing firm power supply.

Storage system selection

The selection of a suitable ESS requires key considerations including but not limited to energy efficiency, energy density, lifecycle, cost per KW and response time. (Chen et al., 2020). Thermal Energy Storage (TES), Battery Energy Storage System (BESS), Pumped Hydrogen Energy Storage (PHES) and Hydrogen Energy Storage (HES) were all reviewed. TOPSIS analysis (see 0) was used to determine the best storage alternative considering all five criteria (listed above), as seen in Table 8. For criteria where attributes fell within a range, upper band figures were selected to maximise output and ensure reliability. For Criteria with only a single inequality value, the values were selected. Response time was weighted on a scale of 4. The ESS with the least response duration was allotted the highest weight and vice versa. The result from the TOPSIS analysis put BESS as the most suitable with the highest relative closeness to the ideal solution of 0.58, which ranked “1”, alongside advantages like rapid response rate, short-term construction, modularity, installation flexibility, and technological maturity. (Zhao Bo, 2018; Zhou et al., 2023) BESS was adopted for the proposed installation.

Table 8 Technical Parameter and TOPSIS ranking for Considered ESS

	TES	BESS	PHES	HES
Efficiency (%)	30-60	75-90	70-80	62-80
Response Time	secs - mins	msec	mins	secs
Lifecycle	N/A	>10000	>15000	>1000
Power Based Cost (\$/KW)	200-300	1200-4000	600 - 2000	500-10000
Relative Closeness to Ideal Solution	0.45	0.58	0.5	0.5
TOPSIS Rank	4	1	2	2

Sources : (Beaudin et al., 2010 ; Bussar et al., 2015; Enescu et al., 2020; Mauler et al., 2021; Zhao Bo, 2018)

Battery energy storage system (BESS) selection

The selection of BESSs was carried out using TOPSIS analysis (see 0). Four widely used and discussed battery energy technologies were considered Vanadium Redox Flow Batteries (VRFB), Lead Acid (PbO₂), Sodium Sulphur (NaS) and Lithium Ion (Li-ion) as alternatives. As displayed in Table 9, attributes for each criterion were retrieved from a wide range of peer-reviewed Scopus index articles and estimated. Upper band figures were selected for criteria

whose attributes fell within inequalities to maximise output and ensure reliability. Technology maturity criteria for each BESS were weighted using a scale of 1 – 4. Mature technologies were allotted 4, commercialised 3, commercialised 2 and developing 1. TOPSIS ranking indicates the smallest Euclidian distance of alternatives to the ideal solution. The ranking from the TOPSIS analysis gave Vanadium Redox Flow Battery and Sodium Sulphur as the joint best alternative amongst all four considered BESS. The VRFB was selected due to its proposed application in offshore wind and increasing global interest (Bai & Song, 2023).

Table 9 Battery Selection Criteria and TOPSIS Rankings

	Li-ion	PbO ₂	NaS	VRFB
Energy Efficiency (%)	> 95	75-80	80	>85
Specific Energy (Wh/kg)	300	180	760	20
Long cycle Life	3000	2000	4000	5000
Depth of Discharge (DOD) (%)	80	80	100	100
Energy Capital Cost \$ (kWh)	600-2500	300-600	>1000	600-1500
Power Capital cost per \$ (kWh)	1200-4000	200-400	300-500	150-1000
Technology Maturity	Commercialised	Commercialised	Commercialised	Commercialising
Response Time	Seconds	Seconds	Seconds	Seconds
TOPSIS Ranking	2	3	1	1

Sources: (Ali et al., 2018; Chen et al., 2020; Gangopadhyay et al., 2024; Jafta, 2022; Locatelli et al., 2015; Nikolaidis & Poullikkas, 2018; F. K. Wang et al., 2022; Zhao Bo, 2018)

Methodology for designing and configuring VRFB-based energy storage systems

Working principles of vanadium redox flow batteries

The employment of Battery has rapidly increased due to scalability, durability and low maintenance (Beaudin et al., 2010; Ibrahim et al., 2008). Vanadium redox flow batteries

(VRFB) are some of the most used (RFB) batteries. VRFBs comprise positive and negative electrolytes coupled with positive and negative electrodes. VRFB act as a fuel cell employing oxidation-reduction reactions to charge and discharge cells. As illustrated in Figure 5. During the charge cycle, the positive electrode pump circulates the positive electrolyte through the collector into the cell stack/power source. Current flows from the positive to the negative electrode, and the positive electrolytes lose an electron while the negative electrolytes gain one. During discharge cycles, the reverse is the case; the negative electrolyte is circulated through the cell stack/power source by the negative electrode pump, and the negative electrolytes lose an electron, and the positive electrolyte gains one. The current capacity of the VRFB is improved by increasing the total number of cells in a stack, and multiple cell stacks are used to increase the voltage of the storage system (Baxter, 2007; Lourenssen et al., 2019; Menictas Chris, 2015).

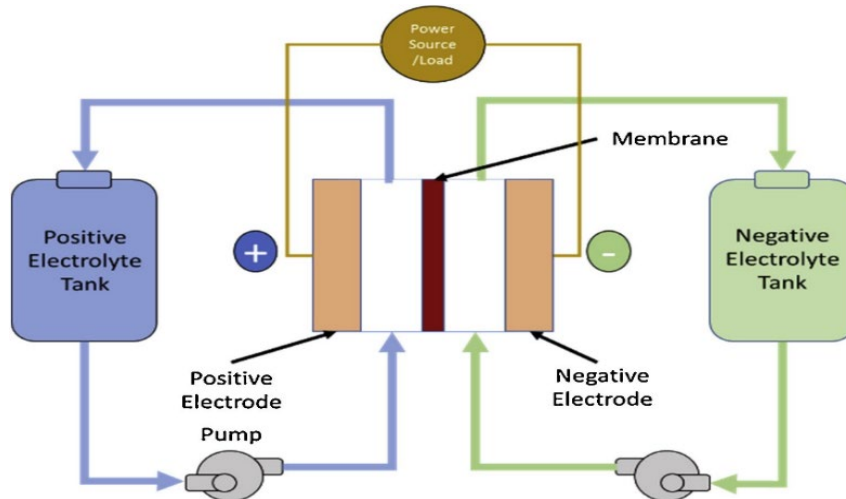


Figure 5 Working Principle of a VRFB

Sources: (Lourenssen et al., 2019)

VRFB Cell Selection and BESS Design Methodology

VRFB cells with nominal cell voltage (V_{Cell}) 1.4 Vdc, cell power 200 W, internal resistance (R_{cell}) 0.001 ohms and maximum cell current (I_{Cell}) 10 A at 1C were selected for the proposed study as outlined in Table 11 (Luo et al., 2015). A desired bank voltage of 132,000 Vdc was assumed to meet transmission voltage regulations in Nigeria. (Babatunde et al., 2023). BESS can be connected in parallel and series to optimise required results; therefore, in estimating the storage design, the number of cells in series (N_s) and parallel (N_p) were evaluated as a factor of the BESS power capacity P_{BESS} using 14 & 15 (Ter-Gazarian, 2020; Zhao Bo, 2018)

$$N_s = V_{\text{BESS}}/V_{\text{Cell}} \quad 14$$

$$N_p = \frac{I_{\text{BESS}}}{I_{\text{Cell}}} = N_s = P_{\text{BESS}} \times R_{\text{cell}} / V_{\text{BESS}} \times V_{\text{cell}} \quad 15$$

Design Methodology for BESS

Electrical energy is converted and stored as chemical energy in a Battery Energy Storage system (BESS) (Zhao Bo, 2018). The design of a BESS commences with the determination of intended capacity, ergo, in designing the proposed BESS, the daily surplus energy E_{SBESS} and deficit E_{DBESS} were estimated by the summation of excess and deficit power per hour as displayed in Table 10.

BESS energy requirement E_{RBESS} was calculated to ensure optimal charge and discharge using 16 and 17.

$$E_{\text{SBESS}} > E_{\text{DBESS}}, \quad E_{\text{RBESS}} = E_{\text{SBESS}} \quad 16$$

$$E_{\text{SBESS}} < E_{\text{DBESS}}, \quad E_{\text{RBESS}} = E_{\text{DBESS}} \quad 17$$

The duration of required energy t_r was approximated by the summation of each hour per day with deficit power as illustrated in Figure 4. The required power P_{RBESS} was estimated using E_{RBESS} and t_r . System reliability was improved by adopting 20 % spare BESS capacity (Ter-Gazarian, 2020) and a 1 h time allowance t_A as indicated in Table 11 to get system power capacity P_{BESS} and total duration t_{BESS} (18 & 19) respectively. Proposed system energy capacity E_{BESS} was estimated as a factor of BESS capacity P_{BESS} and total duration t_{BESS} (20).

$$t_{\text{BESS}} = t_A + t_r \quad 18$$

$$P_{\text{BESS}} = E_{\text{RBESS}} + (E_{\text{RBESS}} \times 0.2) \quad 19$$

$$E_{\text{BESS}} = P_{\text{BESS}}/t_{\text{BESS}} \quad 20$$

Table 10 Power Generation, Excess and Deficit

Time	Expected Power Generation (MW)	Power Generated (MW)	Excess Power Generated (MW)	Power Deficit (MW)
0	354.02	392.96	38.94	-
1	354.02	396.50	42.48	-
2	354.02	392.96	38.94	-
3	354.02	378.80	24.78	-
4	354.02	364.64	10.62	-
5	354.02	346.94	-	7.08
6	354.02	332.78	-	21.24
7	354.02	322.16	-	31.86
8	354.02	311.54	-	42.48
9	354.02	304.46	-	49.56
10	354.02	304.46	-	49.56
11	354.02	304.46	-	49.56
12	354.02	300.92	-	53.10
13	354.02	311.54	-	42.48
14	354.02	332.78	-	21.24
15	354.02	343.40	-	10.62
16	354.02	350.48	-	3.54
17	354.02	357.56	-	-
18	354.02	364.64	10.62	-
19	354.02	375.26	21.24	-
20	354.02	385.88	31.86	-
21	354.02	396.50	42.48	-
22	354.02	410.66	56.64	-
23	354.02	421.28	67.26	-
Total			385.88 MWh / day	382.34 MWh / day

Table 11 Technical Parameter of Battery Storage

Description	Value	Reference
Energy Requirement (MWh)	382.34	
Required Duration (h)	7	
Spare Capacity (%)	20	(Ter-Gazarian, 2020)
Duration Allowance (h)	1	
Cell Voltage (V)	1.4	(Luo et al., 2015)
Cell Power (Wdc)	200	
Cell Internal Resistance (ohms)	0.001	(Lai & McCulloch, 2017)
Battery Mass (Wh/Kg)	20	(Nikolaidis & Poullikkas, 2018)
Cycles per day (100 % DOD)	1	(da Silva Lima et al., 2021)
Cycle lifetime	10000	(Bai & Song, 2023)
Days of Operation	350	
Round Trip Efficiency (%)	83	(Bai & Song, 2023)
Response Time	<1/4 cycle	(Beaudin et al., 2010)
Cycles per day (100 % DOD)	1	(da Silva Lima et al., 2021)
Depth of Discharge	100	(Bai & Song, 2023)
Maximum C-rate	0.125C	(Bai & Song, 2023)

Economic Assessment of ESS Integrated Wind Farm

The Apex of energy production projects provides clean, quality, sustainable, cost-effective electrical energy (Chen et al. 2020). Ergo, there is a need to perform an economic assessment of all energy systems. In this proposed study, The Capital Expenditure (CAPEX), Operational Expenditure (OPEX), Levelised Cost of Energy (LCOE), and Levelised Cost of storage (LCOS) were estimated for the OFWF and BESS using retrieved financial parameters from a wide range of peer-reviewed Scopus index articles as reported in Table 12. LCOE and LCOS - economic parameters used to compare system performance and cost over a lifetime (n) - were estimated as factors of Initial capital cost (I_0), O&M cost for ear “t” ($O\&M_t$), interest rate (i),

degradation factor (d_r) and Energy production for year “t” (EP_t) using System Advisory Model (SAM) (Bai and Song 2023; Gupta et al. 2020; Lai and McCulloch 2017; Giap et al. 2022; Attabo et al. 2023).

CAPEX and OPEX, respectively, as reported in Table 12, were estimated using retrieved capital and O&M cost per KW for utility-scale power plants at 4375 \$/KW and 110 \$/kW – Year for OFWF and 208 \$/kWh and 28 \$/kW – Year for BESS (Energy Information Administration 2020; Bai and Song 2023; da Silva Lima et al. 2021). OFWF civil, mechanical, electrical, indirect, EPC, contingency and owner costs were also evaluated as fractions of the capital cost, as seen in Table 12. (Energy Information Administration 2020).

Table 12 Cost Parameter for Offshore Wind Farm

Component	OFWF	BESS	Reference
Capital Cost (\$/KW)	4375		(Energy Information Administration 2020)
Capital Cost (\$/kWh)		208 (8h)	(Bai and Song 2023)
Civil/Structural Costs	(13.8 % of CAPEX)		(Energy Information Administration 2020)
Mechanical Costs	(44.5 % of CAPEX)		(Energy Information Administration 2020)
Electrical Costs	(19.1 % of CAPEX)		(Energy Information Administration 2020)
Project Indirect Costs	(4.2 % of CAPEX)		(Energy Information Administration 2020)
EPC fee	(4.9 % of CAPEX)		(Energy Information Administration 2020)
Project Contingency Costs	(9.1 % of CAPEX)		(Energy Information Administration 2020)
Owner Costs	(4.3 % of CAPEX)		(Energy Information Administration 2020)
O&M (\$/kW - Year)	110		(da Silva Lima et al. 2021)
Degradation rate (%/Year)		28	(Pawel 2014)
Project Lifetime (Years)	25	0.01	(Luo et al. 2015)
Interest rate (i) (%)	18.75	20	(Trading Economics 2023)
Inflation rate (r) (%)	26.72	18.75	(Central Bank of Nigeria, 2023)

Environmental assessment

Global interest and investment in renewable energy integration are focused on reducing GHG emissions from the atmosphere. CO₂ emissions are harmful to human health and the environment and pose a threat to human existence; thus, it is important to carry out economic analysis on all Power production project (G. K. Akporhonor, Otuagoma, and Akporhonor 2023). Global Warming potential (GWP) is a parameter used to expound the carbon emission of a system. According to the authors' Renewable energy systems do not produce environmental air pollution. Nevertheless, emissions from manufacturing and installation, Operation and maintenance, and decommissioning cannot be ignored (Letcher 2023; Bai and Song 2023; Energy Information Administration 2020). The Environmental Impact Assessment (EIA) of the proposed system was evaluated and compared with other systems at the same annual energy production using retrieved cradle-to-grave (c2g) GWP indicated in Table 13.

Table 13 Components of Environmental Impact Assessment

Components	Life Cycle GWP (g CO ₂ eq/KW)	Reference
OFWF	8	(Lovegrove Keith 2021)
OFWF and BESS	136	(Lovegrove Keith 2021)
Coal Fire Plants	865	(IEA 2020)
Hydropower	11	(Lovegrove Keith 2021)
Onshore wind	10	(Lovegrove Keith 2021)
Solar PV (Open Space)	109	(Lovegrove Keith 2021)
Nuclear Power	14	(Lovegrove Keith 2021)
Natural Gas	600	(Parliamentary Office of Science and Technology 2006)

Results

Energy Storage Integrated Offshore Wind Farm

Figure 6 Depicts a schematic diagram of the generation, transmission, and distribution phases of the proposed 1 GW offshore wind farm integrated with a 66 MW 8 h VRFB capacity. OFWF + BESS commences operation to produce firm power at the wind turbine generator mounted in the rotor nacelle assembly powered by wind speed - rotor blade interaction. Generated power from all 477 turbines is stepped up by turbine transformers, usually located at the base of wind towers and transmitted to offshore substations (OFSS) using inter-array cables. Two OFSSs were proposed in this study to prevent single-point failures. Power is further transmitted at 330 KV to the Sapele 330 / 132 KV onshore transmission substation (TSS) through exporting cables and stepped down to 132 KV during excess power supply and converted to DC to be stored in the Battery Energy Storage System using reversible transformers, reversible inverters and battery management systems encapsulated with charger controllers and SCADA. Excess power is converted back to DC and retrieved from BESS during wind speed lulls to maintain supply voltage frequency at 50 Hz (+/- 0.2 %) and guarantee firm. Power transmission continues to secondary transmission lines and substations closer to the distribution substation (DSS) to reduce voltages as the power approaches users. At DSSs, the power is transferred to street transformers and further to domestic users. Renewable energy integration requires power electronic systems, and the inculcation of a battery energy storage system demands a smart grid to maximise output and ensure seamless operation. (Salee & Wirasanti, 2018). Thus, the current Nigerian grid would require a revamp to integrate the proposed system.

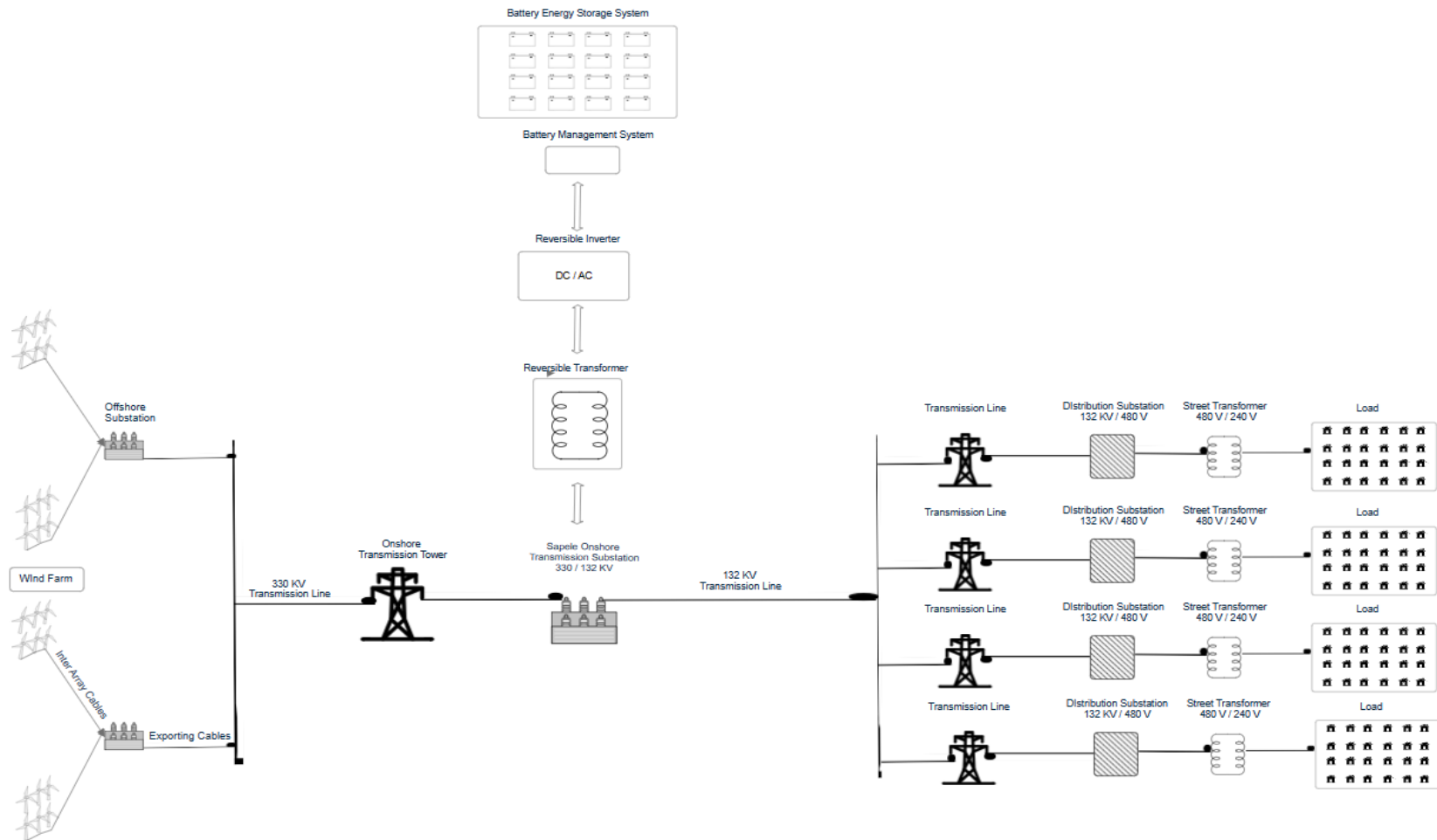


Figure 6 Schematic Diagram of Offshore Wind Farm with Battery Energy Storage System Integration

Technical Assessment for BESS Design

Table 14 Outlines results of BESS design estimation. Total daily energy surplus E_{SBESS} was estimated at 385.88 MWh, and the energy deficit E_{DBESS} at 382.34 MWh. Daily surplus energy was found to be lower than daily energy deficit, thus E_{SBESS} was adopted as a BESS energy requirement E_{RBESS} to guarantee a firm supply of an estimated power output of about 354 MW daily. The required power of the BESS system was evaluated at 55 MW; when escalated by the 20 % spare capacity, the BESS power capacity used to design the system was 66 MW. Alongside an extra 1 h, the aggregate duration of the system became 8 h, and the estimated BESS energy capacity was concluded at 528 MWh. The total number of VRB cells in series was estimated at 94,286, and cells in parallel 50. All cells in series were put in a single stack; thus, 50 sets of VRB were proposed, resulting in a total of 4,714,300 cells.

Table 14 Results of Technical Analysis for VRB Battery Design

Description	Values
Daily Energy surplus (MWh)	385.88
Daily Energy Deficit (MWh)	382.34
Duration of required energy (h)	7
Required Storage Capacity (MWh)	385.88
Required Power Capacity (MW)	55
Estimated BESS Power capacity (MW)	66
Estimated BESS Energy Capacity (MWh)	528
Estimated Time at Maximum Power (h)	8
Desired Storage Bank Voltage (KV)	132
Estimated BESS Current (A)	500
Estimated Number of cells in series	94286
Estimated Number of Cells in Parallel	50
Estimated Total Number of cells	4714300
Estimated Cells Per Stacks	94286
Estimated Stacks in Series	1
Estimated Stacks in Parallel	50

Economic Assessment of the System

Economic assessment estimation of proposed systems displayed LCOE at 393.35 \$/MWh and LCOS at 532.21 \$/MWh, as indicated in Table 15. OFWF LCOE showed great similarity with the proposed global LCOE from newly commissioned offshore wind farms at 393.0 \$/MWh, as suggested by the International Renewable Energy Agency (2021). LCOS and LCOE comparison indicated more cost per kWh for the BESS than the OFWF, owed to factors like low wind speed across the proposed location averaging at 5.2 m/s as well as low-capacity factor at 0.31 of selected turbines across OFL2. CAPEX and OPEX were also found at 1548.75 \$M & 8.94 \$M/ Year for the wind farm and 109.82 \$M & 1.72 \$M/ Year for VRFB storage, as seen in Table 12. OFWF Civil / Structural, Mechanical, Electrical, Indirect, EPC, Contingency and Owner Costs were estimated at 213.73 \$M, 689.19 \$M, 295.81 \$M, 65.05 \$M, 75.89 \$M, 140.94 \$M and 66.60 \$M respectively as displayed in Figure 7.

Table 15 Results from Economic Analysis

LCOE (\$/MWh)	LCOS (\$/MWh)	BESS CAPEX (\$M)	BESS OPEX (\$M - Year)	OFWF CAPEX (\$M)	OFWF OPEX (\$M - Year)
393.35496	532.21	109.824	1.716	1548.75	38.94

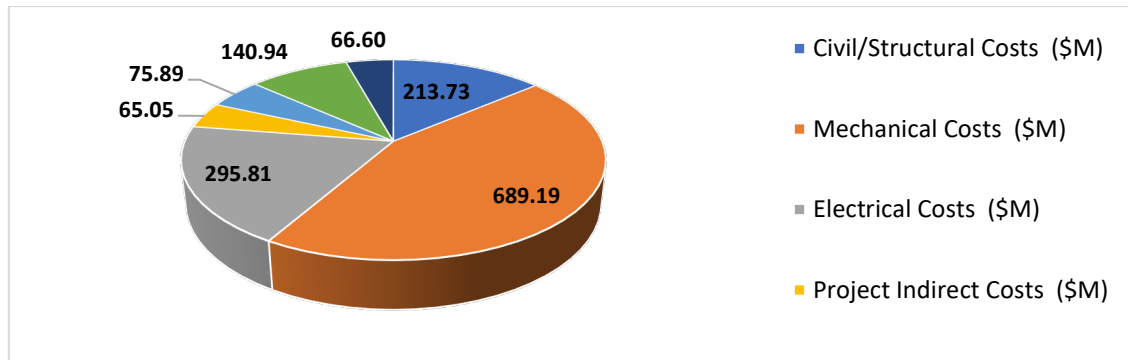


Figure 7 Fractions of OFWF CAPEX

Environmental Assessment of System

EIA results, as illustrated in Figure 8, show massive carbon savings by siting the proposed OFWF without a battery system as opposed to all other considered systems. However, including BESS increases CO₂ emission by over 70 %, only better than Coal fire plants at 804450 mt CO₂ eq, Natural gas at 558000 mt CO₂ eq and Open space PV at 101370 mt CO₂ eq.

Additionally, the proposed system saves over 107 % and 74 % of carbon emissions compared to coal fire and natural gas power plants of the same capacity.

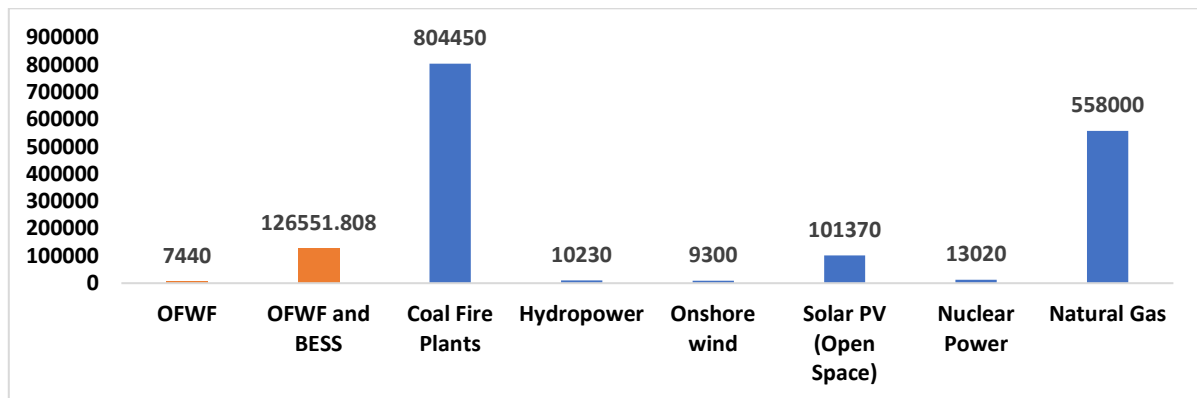


Figure 8 GWP (mt CO₂ eq) Comparison between Proposed System and Conventional Systems.

Discussion and Recommendation

Environmental implications

The integration of battery energy storage into offshore wind farms offers substantial environmental benefits, particularly in terms of carbon savings. This approach allows Nigeria to significantly reduce its carbon footprint, supporting the nation's Nationally Determined Contribution (NDC) under the Paris Agreement. By incorporating these technologies into the country's energy infrastructure, Nigeria can move closer to achieving a 36% renewable energy share by 2030 (IEA, 2013) while addressing the challenge of energy curtailment. However, as with any renewable energy technology, offshore wind farms come with their environmental implications. These systems can contribute to issues like releasing endogenous pollutants, water stratification, and sediment-water interference throughout their lifecycle. While the operation of offshore wind farms generally has minimal impact on marine ecosystems, construction phases can be more disruptive, particularly to marine life. Studies suggest that the most notable effects occur during the installation phase, with disturbances to the migration of seabirds and marine mammals being relatively minimal (Lloret et al., 2022). Furthermore, installing wind turbines may disturb the benthic flora and fauna, vital to the ecological balance of marine environments. However, there is insufficient data to determine whether these impacts pose a significant threat to the survival of marine communities, indicating a need for further research on the long-term ecological effects of offshore wind farms across different marine environments. Despite these potential challenges, the greenhouse gas reductions provided by

offshore wind systems are significant, especially when compared to traditional fossil fuel-based energy sources such as coal and natural gas. The lifecycle analysis of offshore wind technology consistently shows that it offers favourable carbon savings, further supporting its role in helping countries like Nigeria meet climate goals. Nigeria can significantly reduce the potential negative environmental impacts by adopting mitigation strategies, such as better construction timing to avoid critical migration periods and using noise-dampening technologies to reduce disturbances to marine mammals. Ultimately, while there are environmental risks associated with offshore wind farms, the climate benefits they provide far outweigh these challenges, positioning them as a key solution in Nigeria's energy transition towards a more sustainable future.

Social–Economic implications

Considering the socio-economic impact, the estimated Levelised Cost of Energy (LCOE) for the proposed 1 GW offshore wind farm at 393.35 \$/MWh in the Koko Sea coastal area is similar to the global LCOE of 393.0 \$/MWh. This makes it a viable option. However, when compared to the Levelised Cost of Supply (LCOS) of conventional sources such as coal and gas, which are 116 \$/MWh and 91 \$/MWh respectively (IEA, 2020a), the costs appear higher.

These median LCOE calculations, evaluated using the discounted cash flow method, aggregate data from 24 countries and do not tell the whole story due to the varying factors considered, including cost, site availability, and technology maturity across a specific region like Nigeria. (IEA, 2020a). Nonetheless, as technology advances, the cost of clean energy sources is gradually reducing. This trend is illustrated by the "Levelised Cost of Energy by Technology, World" chart from (Our World in Data, 2022), which shows a steady decline in clean energy LCOE from 2015 to 2022.

Study Limitation

In site selection for offshore wind, the two main constraints were Shore distance and depth of water. According to Laura and Vicente (2014), over 60 % - 80 % of offshore wind potential is in water depths over 60 m. Constructing conventional fixed offshore foundations is more technically and fiscally difficult to install. In the selection of OFL 2, our location was limited to shallower water depth and closer regions to the shoreline to reduce cost and maximise output. Nevertheless, the limitation of water depth has led to technological advances and investigation in floating offshore wind aimed at cost optimisation (Yang et al. 2023; Zhou et al. 2023). This

rise in the cost of siting offshore wind in deeper waters and low readiness of floating offshore technologies limited our focus to locations with lower water depths closer to the shoreline.

Recommendations

To strengthen Nigeria's energy system, it is recommended that battery storage be implemented on integrated offshore wind farms. This approach will ensure a stable power supply, reduce carbon emissions, and enhance the economic viability of Nigeria's energy sector. The integration of battery storage addresses the intermittent nature of wind energy, offering consistent power delivery. Therefore, greater investment and initiatives should be directed towards exploring the potential of such installations. Strategic decisions to advance and actualise this technology will yield substantial environmental and economic benefits, aligning with Nigeria's commitments under the Paris Agreement and Sustainable Development Goals (SDGs).

Policy Recommendations

The following policy recommendations are made to promote the successful development of battery-integrated offshore wind farms in Nigeria, focusing on financing, infrastructure, and regulatory frameworks.

- **Financing Initiatives:** To address the high capital intensity of offshore wind projects, Nigeria should adopt financial mechanisms to de-risk private investments and facilitate access to low-cost finance. The government should introduce concessional loans and loan guarantees through the Central Bank of Nigeria (CBN) and development finance institutions such as the African Development Bank (AfDB). Additionally, Nigeria could issue green bonds to mobilise funds for offshore wind development, following the successful models of Morocco and South Africa. Public-private partnerships (PPPs) should also be pursued to finance offshore wind infrastructure, reducing public expenditure while attracting private sector investment (U.S. Department of Energy, 2024; WFO-Global, 2022).
- **Infrastructure Development:** To ensure a stable power supply and efficient power evacuation, investment is needed in Nigeria's transmission and port infrastructure. Upgrades to port facilities in Lagos, Port Harcourt, and Warri will support the transportation and assembly of large offshore wind turbine components. Simultaneously, modernising the national grid with smart grid technology and high-voltage direct current (HVDC) systems will allow offshore wind farms to be seamlessly

integrated into Nigeria's power system. Offshore substations should be developed in partnership with the private sector, leveraging public-private financing models (BusinessDay, 2022).

- **Regulatory Framework:** The Nigerian government should establish a one-stop permitting process to streamline licensing for offshore wind projects. A proposed Offshore Renewable Energy Authority (OREA) would act as a centralised agency for processing permits, licences, and approvals, reducing bureaucratic delays. Additionally, Nigeria should develop a Marine Spatial Plan (MSP) to designate priority areas for offshore wind development, minimising conflicts with fisheries, marine traffic, and conservation areas. To protect marine biodiversity, regulations should require Environmental Impact Assessments (EIAs) to assess potential impacts on marine life and specify mitigation measures (Ojo, 2017; Nwafor, 2022).

Developing battery-integrated offshore wind farms is vital to Nigeria's energy security and sustainability goals. By addressing key areas of financing, infrastructure, and regulatory frameworks, Nigeria can unlock the economic and environmental benefits of offshore wind energy. These initiatives support Nigeria's obligations under the Paris Agreement and contribute to achieving the Sustainable Development Goals (SDGs), fostering a clean energy future for the nation.

Conclusion

The proposed study attempted to conduct a techno-economic and environmental assessment (TEEA) of siting a storage-integrated wind farm across Nigerian offshore locations to provide reliable and accurate information that would aid relevant stakeholders in making critical decisions on energy transition.

Three offshore locations near Nigeria's south-south coastal line were evaluated considering aggregate wind speed, shore distance and water depth. OFL2, with a mean wind speed of 3.98 m/s at a height of 10 m, was selected as the most suitable site. A 1 GW capacity was nominated, putting into view the Nigerian electricity profile, low electrification rate, increasing energy demand, population growth rate, unequivocal demand and supply chart, as well as global suggestions for all new offshore wind farms to be capped at a minimum of 1 GW to facilitate the "2000 GW installed offshore capacity by 2050 goal". IEC III low wind speed SG 2.1/114

turbine, with cut-in, rated and cut-off wind speeds of 3 m/s, 9 m/s, and 23 m/s, respectively, was adopted and 477 “SG 2.1/114 turbines” were estimated to match intended OFWF capacity.

The need for an energy storage system was justified, and a suitable ESS was selected from thermal Energy storage battery energy storage system, pumped hydro energy storage and hydrogen energy storage. Power-based cost, lifecycle, response time, energy density and efficiency were considered criteria and employing a TOPSIS analysis, BESS was selected as the most suitable. Vanadium redox flow batteries were adopted amongst other BESS, ranking highest in an MCDM analysis. Li-on, NaS, and PbO were the other considered battery systems. Energy Efficiency, Specific Energy, Long cycle Life, Depth of Discharge, Energy Capital Cost, Power Capital cost, Technology Maturity, and Response Time were the evaluated criteria.

Furthermore, a technical, economic and environmental analysis was carried out to integrate a VRFB into the proposed 1 GW wind farm across offshore Nigeria, resulting in the following key outlines.

- Power output (P_{OFWF}) and annual energy production (EP_{OFWF}) of OFWF were evaluated at turbine hub height 150 m using retrieved capacity factor, coefficient of performance, estimated losses and results displayed P_{Out} at 0.35 GW and EP_{OFWF} at 930 GWh.
- A storage need of 55 MW for 7 hours (382MWh) was identified.
- Technical estimation identified a VRB design of 66 MW for 8 hours (528 MWh) after considering system allowances.
- A single-cell stack of 94286 cells in series and 50 cell stacks in parallel was approximated to give the desired energy and voltage output.
- The LCOE of the proposed system indicated values similar to those of the global LCOE for newly commissioned offshore wind farms in 2020.
- EIA results displayed significant carbon savings of over 107 % and 74 % for coal and natural gas power plants of the same capacity, respectively.

In summary, integrating battery energy storage with offshore wind farms in Nigeria offers significant environmental and socio-economic benefits. This approach can substantially reduce the country's carbon footprint, helping Nigeria meet its Nationally Determined Contribution under the Paris Agreement and achieve its goal of generating 36% renewable energy by 2030. While offshore wind farms have some environmental impacts, such as

potential disturbances to marine life, the overall benefits of reducing greenhouse gas emissions are considerable. Economically, although the Levelised Cost of Energy (LCOE) for offshore wind is currently higher than for conventional energy sources, the declining costs of clean energy technologies are promising. Therefore, investing in battery-integrated offshore wind farms and pursuing further initiatives to support their development and implementation in Nigeria is recommended.

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References

- Abam, F. I., & Ohunakin, O. S. (2018). Applications of small-scale, stand-alone wind energy conversion systems in rural Cross River State, Nigeria. *African Journal of Science, Technology, Innovation and Development*, 10(5), 539–550. <https://doi.org/10.1080/20421338.2017.1366134>
- Abdullahi, Y., & Kehinde, A. O. (2023). Drivers, Enablers, Barriers and Technologies (DEBT) For Low-Energy Public Housing Delivery in Nigeria. *Journal of Advanced Research in Applied Sciences and Engineering Technology*, 29(3), 115–127. <https://doi.org/10.37934/ARASET.29.3.115127>
- Abu Dabous, S., & Alkass, S. (2008). Decision support method for multi-criteria selection of bridge rehabilitation strategy. *Construction Management and Economics*, 26(8), 883–893. <https://doi.org/10.1080/01446190802071190>
- Adoghe, A. U., Adeyemi-Kayode, T. M., Oguntosin, V., & Amahia, I. I. (2023). Performance evaluation of the prospects and challenges of effective power generation and distribution in Nigeria. *Heliyon*, 9(3), e14416. <https://doi.org/10.1016/J.HELIYON.2023.E14416>
- Ajayi, O., & Katende, J. (2011). Assessment of Wind Power Potential and Wind Electricity Generation Using WECS of Two Sites in South West, Nigeria. *International Journal of Energy Science*, 1.
- Akporhonor, G. K., Otuagoma, S. O., & Akporhonor, T. A. (2023). Nigerian wind energy status. <https://doi.org/10.1177/0309524X231206559>
- Akporhonor Gbubemi Kevin, & Otuagoma, S. O. (2023). *Wind Energy Assessment: Data Retrieval, Periodicity, and Time Series*. 27, 43–54.
- Al-Addous, M., Jaradat, M., Albatayneh, A., Wellmann, J., & Al Hmidan, S. (2020). The Significance of Wind Turbines Layout Optimization on the Predicted Farm Energy Yield. *Atmosphere* 2020, Vol. 11, Page 117, 11(1), 117. <https://doi.org/10.3390/ATMOS11010117>
- Alham, M. H., Fathy Gad, M., & Khalil Ibrahim, D. (2023). Potential of wind energy and economic assessment in Egypt considering optimal hub height by equilibrium optimizer. *Ain Shams Engineering Journal*, 14(1). <https://doi.org/10.1016/j.asej.2022.101816>

- Ali, M., Ekström, J., & Lehtonen, M. (2018). Sizing Hydrogen Energy Storage in Consideration of Demand Response in Highly Renewable Generation Power Systems. *Energies* 2018, Vol. 11, Page 1113, 11(5), 1113. <https://doi.org/10.3390/EN11051113>
- Ambrose, H., & Kendall, A. (2016). Effects of battery chemistry and performance on the life cycle greenhouse gas intensity of electric mobility. *Transportation Research Part D: Transport and Environment*, 47, 182–194. <https://doi.org/10.1016/J.TRD.2016.05.009>
- Ashuri, T., Ponnuram, C., Zhang, J., & Rotea, M. (2016). Integrated Layout and Support Structure Optimization for Offshore Wind Farm Design. *Journal of Physics: Conference Series*, 753(9), 092011. <https://doi.org/10.1088/1742-6596/753/9/092011>
- Attabo, A. A., Ajayi, O. O., Oyedepo, S. O., & Afolalu, S. A. (2023). Assessment of the wind energy potential and economic viability of selected sites along Nigeria's coastal and offshore locations. *Frontiers in Energy Research*, 11. <https://doi.org/10.3389/fenrg.2023.1186095>
- Attah, A. R., Abubakar, J., & Badejo, J. (2021). Assessing the Technical Offshore Wind Energy Potential in Lagos, Nigeria. *IOP Conference Series: Earth and Environmental Science*, 730(1), 012036. <https://doi.org/10.1088/1755-1315/730/1/012036>
- Ayodele, T. R., Ogunjuyigbe, A. S. O., & Amusan, T. O. (2016). Wind power utilization assessment and economic analysis of wind turbines across fifteen locations in the six geographical zones of Nigeria. *Journal of Cleaner Production*, 129, 341–349. <https://doi.org/10.1016/J.JCLEPRO.2016.04.060>
- Babatunde, O., Buraimoh, E., Tinuoye, O., Ayegbusi, C., Davidson, I., & Ighravwe, D. E. (2023). Electricity sector assessment in Nigeria: the post-liberation era. *Cogent Engineering*, 10(1). <https://doi.org/10.1080/23311916.2022.2157536>
- Bai, H., & Song, Z. (2023). Lithium-ion battery, sodium-ion battery, or redox-flow battery: A comprehensive comparison in renewable energy systems. *Journal of Power Sources*, 580, 233426. <https://doi.org/10.1016/J.JPOWSOUR.2023.233426>
- Bamisile, O., Huang, Q., Xu, X., Hu, W., Liu, W., Liu, Z., & Chen, Z. (2020). An approach for sustainable energy planning towards 100 % electrification of Nigeria by 2030. *Energy*, 197, 117172. <https://doi.org/10.1016/J.ENERGY.2020.117172>

- Baxter, R. (2007). Zinc Bromine. In *Energy Storage - A Nontechnical Guide*. PennWell.
<https://app.knovel.com/hotlink/khtml/id:kt008MZ175/energy-storage-nontechnical/flow-batte-zinc-bromine>
- Beaudin, M., Zareipour, H., Schellenberglobe, A., & Rosehart, W. (2010). Energy storage for mitigating the variability of renewable electricity sources: An updated review. *Energy for Sustainable Development*, 14(4), 302–314. <https://doi.org/10.1016/J.ESD.2010.09.007>
- Ben, U. C., Akpan, A. E., Mbonu, C. C., & Ufuafuonye, C. H. (2021). Integrated technical analysis of wind speed data for wind energy potential assessment in parts of southern and central Nigeria. *Cleaner Engineering and Technology*, 2. <https://doi.org/10.1016/j.clet.2021.100049>
- Bird, L., Lew, D., Milligan, M., Carlini, E. M., Estanqueiro, A., Flynn, D., Gomez-Lazaro, E., Holttinen, H., Menemenlis, N., Orth, A., Børre Eriksen, P., Smith, J. C., Soder, L., Sorensen, P., Altiparmakis, A., Yasuda, Y., & Miller, J. (2016). *Wind and solar energy curtailment: A review of international experience*. <https://doi.org/10.1016/j.rser.2016.06.082>
- Brunelli, M. (2015). *Introduction to the Analytic Hierarchy Process*. <https://doi.org/10.1007/978-3-319-12502-2>
- BusinessDay. (2022). Nigeria's potential promising as investors turn to wind energy. Retrieved from <https://businessday.ng/energy/article/nigerias-potential-promising-as-investors-turn-to-wind-energy/>
- Bussar, C., Stöcker, P., Cai, Z., Moraes, L., Alvarez, R., Chen, H., Breuer, C., Moser, A., Leuthold, M., & Sauer, D. U. (2015). Large-scale Integration of Renewable Energies and Impact on Storage Demand in a European Renewable Power System of 2050. *Energy Procedia*, 73, 145–153. <https://doi.org/10.1016/J.EGYPRO.2015.07.662>
- Cai, Y., & Bréon, F. M. (2021). Wind power potential and intermittency issues in the context of climate change. *Energy Conversion and Management*, 240, 114276. <https://doi.org/10.1016/J.ENCONMAN.2021.114276>
- Cakiroglu, C., Demir, S., Hakan Ozdemir, M., Latif Aylak, B., Sariisik, G., & Abualigah, L. (2024). Data-driven interpretable ensemble learning methods for the prediction of wind

- turbine power incorporating SHAP analysis. *Expert Systems with Applications*, 237, 121464. <https://doi.org/10.1016/J.ESWA.2023.121464>
- Central Bank of Nigeria. (2023, September). *Central Bank of Nigeria*. <https://www.cbn.gov.ng/>
- Chakraborty, S. (2022). TOPSIS and Modified TOPSIS: A comparative analysis. *Decision Analytics Journal*, 2, 100021. <https://doi.org/10.1016/j.dajour.2021.100021>
- Chen, T., Jin, Y., Lv, H., Yang, A., Liu, M., Chen, B., Xie, Y., & Chen, Q. (2020). Applications of Lithium-Ion Batteries in Grid-Scale Energy Storage Systems. *Transactions of Tianjin University*, 26(3), 208–217. <https://doi.org/10.1007/S12209-020-00236-W/FIGURES/4>
- Cleveland, C. J. (2004). Wind Farm Siting Issues. In *Encyclopedia of Energy, Volumes 1 - 6*. Elsevier. <https://app.knovel.com/hotlink/khtml/id:kt004KXEE1/encyclopedia-energy-volumes/wind-farmsiting-issues>
- Climatescope. (2022). *Nigeria*. <https://www.global-climatescope.org/markets/ng/>
- Cruz, R. O., Duarte, G. R., Pires de Lima, B. S. L., & Jacob, B. P. (2024). Optimization of Steel Jackets to Support Offshore Wind Turbines Using Evolutionary Algorithms. *Journal of Offshore Mechanics and Arctic Engineering*, 146(2). <https://doi.org/10.1115/1.4062625>
- da Silva Lima, L., Quartier, M., Buchmayr, A., Sanjuan-Delmás, D., Laget, H., Corbisier, D., Mertens, J., & Dewulf, J. (2021). Life cycle assessment of lithium-ion batteries and vanadium redox flow batteries-based renewable energy storage systems. *Sustainable Energy Technologies and Assessments*, 46, 101286. <https://doi.org/10.1016/J.SETA.2021.101286>
- Dannheim, J., Bergström, L., Birchenough, S. N. R., Brzana, R., Boon, A. R., Coolen, J. W. P., Dauvin, J. C., De Mesel, I., Derweduwen, J., Gill, A. B., Hutchison, Z. L., Jackson, A. C., Janas, U., Martin, G., Raoux, A., Reubens, J., Rostin, L., Vanaverbeke, J., Wilding, T. A., ... Degraer, S. (2020). Benthic effects of offshore renewables: Identification of knowledge gaps and urgently needed research. In *ICES Journal of Marine Science* (Vol. 77, Issue 3, pp. 1092–1108). Oxford University Press. <https://doi.org/10.1093/icesjms/fsz018>
- Davis, N. N., Badger, J., Hahmann, A. N., Hansen, B. O., Mortensen, N. G., Kelly, M., Larsén, X. G., Olsen, B. T., Floors, R., Lizcano, G., Casso, P., Lacave, O., Bosch, A., Bauwens, I., Knight, O. J., Potter van Loon, A., Fox, R., Parvanyan, T., Krohn Hansen, S. B., ...

- Drummond, R. (2023). The Global Wind Atlas: A High-Resolution Dataset of Climatologies and Associated Web-Based Application. *Bulletin of the American Meteorological Society*, 104(8), E1507–E1525. <https://doi.org/10.1175/BAMS-D-21-0075.1>
- Delina, L. L. (2022). Wind energy in the city: Hong Kong's offshore wind energy generation potential, deployment plans, and ecological pitfalls. *The Electricity Journal*, 35(6), 107139. <https://doi.org/10.1016/J.TEJ.2022.107139>
- Düzcan, A., & Kara, Y. A. (2021). Assessment of wind energy potential: a case study. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*. <https://doi.org/10.1080/15567036.2021.1903119>
- Eboibi, B., Eboibi, O., Okubio, E., & Iyasele, C. (2017). Evaluation of wind energy potential in the south-south geopolitical zone of Nigeria. *Journal of Applied Sciences and Environmental Management*, 21(7), 1301–1306. <https://doi.org/10.4314/JASEM.V21I7.14>
- Energy Information Administration, U. (2020). *Capital Cost and Performance Characteristic Estimates for Utility Scale Electric Power Generating Technologies*. www.eia.gov
- Energy Institute. (2023). *Statistical Review of World Energy Data*.
- Enescu, D., Chicco, G., Porumb, R., & Seritan, G. (2020). Thermal Energy Storage for Grid Applications: Current Status and Emerging Trends. *Energies* 2020, Vol. 13, Page 340, 13(2), 340. <https://doi.org/10.3390/EN13020340>
- Eweka, E. E., Lopez-Arroyo, E., Medupin, C. O., Oladipo, A., & Campos, L. C. (2022). Energy Landscape and Renewable Energy Resources in Nigeria: A Review. In *Energies* (Vol. 15, Issue 15). MDPI. <https://doi.org/10.3390/en15155514>
- Gangopadhyay, A., Seshadri, A. K., & Patil, B. (2024). Wind-solar-storage trade-offs in a decarbonizing electricity system. *Applied Energy*, 353, 121994. <https://doi.org/10.1016/J.APENERGY.2023.121994>
- Giap, V. T., Lee, Y. D., Kim, Y. S., Bui, T., & Ahn, K. Y. (2022). New definition of levelized cost of energy storage and its application to reversible solid oxide fuel-cell. *Energy*, 239, 122220. <https://doi.org/10.1016/J.ENERGY.2021.122220>
- Global Wind Atlas. (2023). *Global Wind Atlas*. <https://globalwindatlas.info/en/>

- Gonen, Turan. E. machines. (2012). *Electrical machines with MATLAB* (2nd ed.). CRC Press.
- Gupta, R., Soini, M. C., Patel, M. K., & Parra, D. (2020). Levelized cost of solar photovoltaics and wind supported by storage technologies to supply firm electricity. *Journal of Energy Storage*, 27, 101027. <https://doi.org/10.1016/J.EST.2019.101027>
- Ibrahim, H., Ilinca, A., & Perron, J. (2008). Energy storage systems—Characteristics and comparisons. *Renewable and Sustainable Energy Reviews*, 12(5), 1221–1250. <https://doi.org/10.1016/J.RSER.2007.01.023>
- IEA. (2013). *Nigeria Renewable Energy Master Plan*. <https://www.iea.org/policies/4974-nigeria-renewable-energy-master-plan>
- IEA. (2020a). *Projected Costs of Generating Electricity 2020 Edition*. <https://www.iea.org/reports/projected-costs-of-generating-electricity-2020>
- IEA. (2020b, June 29). *Average CO₂ intensity of power generation from coal power plants*. <https://www.iea.org/data-and-statistics/charts/average-co2-intensity-of-power-generation-from-coal-power-plants-2000-2020>
- IEA. (2023). *Nationally Determined Contribution (NDC) to the Paris Agreement: Nigeria*. <https://www.iea.org/policies/11784-nationally-determined-contribution-ndc-to-the-paris-agreement-nigeria>
- International Renewable Energy Agency. (2021). *Renewable Power Generation Costs in 2020 Executive Summary*.
- IRENA. (2023a). *Energy Profile (United Kingdom)*.
- IRENA. (2023b). *World Energy Transitions Outlook 2023*. International Renewable Energy Agency. <https://www.irena.org/Digital-Report/World-Energy-Transitions-Outlook-2023>
- Jafta, C. J. (2022). Grid scale energy storage: The alkali-ion battery systems of choice. *Current Opinion in Electrochemistry*, 36, 101130. <https://doi.org/10.1016/J.COEELEC.2022.101130>
- Juan, Y. H., Rezaeiha, A., Montazeri, H., Blocken, B., Wen, C. Y., & Yang, A. S. (2022). CFD assessment of wind energy potential for generic high-rise buildings in close proximity: Impact of building arrangement and height. *Applied Energy*, 321, 119328. <https://doi.org/10.1016/J.APENERGY.2022.119328>

- Jung, C., & Schindler, D. (2020). Introducing a new approach for wind energy potential assessment under climate change at the wind turbine scale. *Energy Conversion and Management*, 225. <https://doi.org/10.1016/j.enconman.2020.113425>
- Lai, C. S., & McCulloch, M. D. (2017). Levelized cost of electricity for solar photovoltaic and electrical energy storage. *Applied Energy*, 190, 191–203. <https://doi.org/10.1016/J.APENERGY.2016.12.153>
- Laura, C. S., & Vicente, D. C. (2014). Life-cycle cost analysis of floating offshore wind farms. *Renewable Energy*, 66, 41–48. <https://doi.org/10.1016/J.RENENE.2013.12.002>
- Lee, W., Park, G., & Kwon, Y. (2023). Cost, Performance, and Sustainability of Redox Flow Batteries Using 4,5-Dihydroxy-1,3-benzenedisulfonic Acid and Vanadium Enhanced by Cross Compensation of the Activation Process. *ACS Sustainable Chemistry and Engineering*, 11, 12458–12466. https://doi.org/10.1021/ACSSUSCHEMENG.3C03316/ASSET/IMAGES/LARGE/SC3C03316_0005.JPEG
- Letcher, T. M. (2023). References. In *Wind Energy Engineering - A Handbook for Onshore and Offshore Wind Turbines (2nd Edition)* (pp. 399–409). Elsevier. <https://app.knovel.com/hotlink/khtml/id:kt013COSUS/wind-energy-engineering/greenhouse-references>
- Li, G., Pu, G., Yang, J., & Jiang, X. (2024). A multidimensional quantitative risk assessment framework for dense areas of stay points for urban HazMat vehicles. *Reliability Engineering and System Safety*, 241, 109637. <https://doi.org/10.1016/j.ress.2023.109637>
- Lloret, J., Turiel, A., Solé, J., Berdalet, E., Sabatés, A., Olivares, A., Gili, J. M., Vila-Subirós, J., & Sardá, R. (2022). Unravelling the ecological impacts of large-scale offshore wind farms in the Mediterranean Sea. *Science of The Total Environment*, 824, 153803. <https://doi.org/10.1016/J.SCITOTENV.2022.153803>
- Locatelli, G., Palmera, E., & Mancini, M. (2015). Assessing the economics of large Energy Storage Plants with an optimisation methodology. *Energy*, 83, 15–28. <https://doi.org/10.1016/J.ENERGY.2015.01.050>

- Lourenssen, K., Williams, J., Ahmadpour, F., Clemmer, R., & Tasnim, S. (2019). Vanadium redox flow batteries: A comprehensive review. *Journal of Energy Storage*, 25, 100844. <https://doi.org/10.1016/J.EST.2019.100844>
- Lovegrove Keith, S. W. (2021). Future Trends. In *Concentrating Solar Power Technology - Principles, Developments, and Applications (2nd Edition)*. Elsevier. <https://app.knovel.com/hotlink/khtml/id:kt012M1K9P/concentrating-solar-power/socio-econ-future-trends>
- Luo, X., Wang, J., Dooner, M., & Clarke, J. (2015). Overview of current development in electrical energy storage technologies and the application potential in power system operation. *Applied Energy*, 137, 511–536. <https://doi.org/10.1016/J.APENERGY.2014.09.081>
- Malaekheh, S. M., Safaie, A., Shiva, L., & Tabari, H. (2022). Spatio-temporal variation of hydro-climatic variables and extreme indices over Iran based on reanalysis data. *Stochastic Environmental Research and Risk Assessment* 2022 36:11, 36(11), 3725–3752. <https://doi.org/10.1007/S00477-022-02223-0>
- Mauler, L., Duffner, F., Zeier, W. G., & Leker, J. (2021). Battery cost forecasting: a review of methods and results with an outlook to 2050. *Energy & Environmental Science*, 14(9), 4712–4739. <https://doi.org/10.1039/D1EE01530C>
- Menictas Chris, S.-K. M. L. T. M. (2015). Vanadium Redox. In *Advances in Batteries for Medium- and Large-Scale Energy Storage*. Elsevier. <https://app.knovel.com/hotlink/khtml/id:kt00U9U0U2/advances-in-batteries/vanadium-redox>
- Mo, J. O., Choudhry, A., Arjomandi, M., & Lee, Y. H. (2013). Large eddy simulation of the wind turbine wake characteristics in the numerical wind tunnel model. *Journal of Wind Engineering and Industrial Aerodynamics*, 112, 11–24. <https://doi.org/10.1016/J.JWEIA.2012.09.002>
- Neupane, D., Kafle, S., Karki, K. R., Kim, D. H., & Pradhan, P. (2022). Solar and wind energy potential assessment at provincial level in Nepal: Geospatial and economic analysis. *Renewable Energy*, 181, 278–291. <https://doi.org/10.1016/J.RENENE.2021.09.027>

- Nikolaidis, P., & Poullikkas, A. (2018). Cost metrics of electrical energy storage technologies in potential power system operations. *Sustainable Energy Technologies and Assessments*, 25, 43–59. <https://doi.org/10.1016/J.SETA.2017.12.001>
- Nwafor, C. (2022). Marine spatial planning for offshore wind development in Nigeria. *Journal of Environmental Policy*, 15(3), 45-67. Retrieved from <https://journals.unilag.edu.ng/index.php/jep/article/view/2022>
- Ohunakin, O. S. (2011). Assessment of wind energy resources for electricity generation using WECS in North-Central region, Nigeria. *Renewable and Sustainable Energy Reviews*, 15(4), 1968–1976. <https://doi.org/10.1016/J.RSER.2011.01.001>
- Ohunakin, O. S., Matthew, O. J., Adaramola, M. S., Atiba, O. E., Adelekan, D. S., Aluko, O. O., Henry, E. U., & Ezekiel, V. U. (2023). Techno-economic assessment of offshore wind energy potential at selected sites in the Gulf of Guinea. *Energy Conversion and Management*, 288, 117110. <https://doi.org/10.1016/J.ENCONMAN.2023.117110>
- Ojo, O. V. (2017). An overview of the legal and regulatory framework for renewable energy projects in Nigeria: Challenges and prospects. *Unilag Law Review*, 1(1). Retrieved from <https://ssrn.com/abstract=2997075>
- Okeniyi, J. O., Moses, I. F., & Okeniyi, E. T. (2015). Wind characteristics and energy potential assessment in Akure, South West Nigeria: econometrics and policy implications. *International Journal of Ambient Energy*, 36(6), 282–300. <https://doi.org/10.1080/01430750.2013.864586>
- Olaofe, Z. O. (2017). Assessment of the Offshore Wind Speed Distributions at Selected Stations in the South-West Coast, Nigeria. In *INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH Z.O. Olaofe* (Vol. 7, Issue 2).
- Onoruoiza, M. R., Adedipe, O., Lawal, S. A., Olugboji, O. A., & Nwachukwu, V. C. (2022). Analysis of offshore wind energy potential for power generation in three selected locations in Nigeria. *African Journal of Science, Technology, Innovation and Development*, 14(3), 774–789. <https://doi.org/10.1080/20421338.2021.1899760>
- Our World in Data. (2022). *Levelized cost of energy by technology, World*. <https://ourworldindata.org/grapher/levelized-cost-of-energy>

- Owebor, K., Diemuodeke, O. E., Briggs, T. A., Eyenubo, O. J., Ogorure, O. J., & Ukoba, M. O. (2022a). Multi-criteria optimisation of integrated power systems for low-environmental impact. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 44(2), 3459–3476. <https://doi.org/10.1080/15567036.2022.2064565>
- Owebor, K., Diemuodeke, O. E., Briggs, T. A., Eyenubo, O. J., Ogorure, O. J., & Ukoba, M. O. (2022b). Multi-criteria optimisation of integrated power systems for low-environmental impact. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 44(2), 3459–3476. <https://doi.org/10.1080/15567036.2022.2064565>
- Oyewole, J. A., & Aro, T. O. (2018). Wind speed pattern in Nigeria (a case study of some coastal and inland areas). *Journal of Applied Sciences and Environmental Management*, 22(1), 119–123. <https://doi.org/10.4314/JASEM.V22I1.22>
- Pagnani, D., Kocewiak, Ł., Hjerrild, J., Blaabjerg, F., & Bak, C. L. (2023). Integrating black start capabilities into offshore wind farms by grid-forming batteries. *IET Renewable Power Generation*, 17(14), 3523–3535. <https://doi.org/10.1049/RPG2.12667>
- Paraschiv, S., Paraschiv, L. S., Serban, A., & Cristea, A. G. (2022). Assessment of onshore wind energy potential under temperate continental climate conditions. *Energy Reports*, 8, 251–258. <https://doi.org/10.1016/J.EGYR.2022.02.118>
- Parliamentary Office of Science and Technology. (2006). *Carbon Footprint of Electricity Generation*.
- Patidar, H., Shende, V., Baredar, P., & Soni, A. (2022). Comparative study of offshore wind energy potential assessment using different Weibull parameters estimation methods. *Environmental Science and Pollution Research*, 29(30), 46341–46356. <https://doi.org/10.1007/s11356-022-19109-x>
- Pawel, I. (2014). The Cost of Storage – How to Calculate the Levelized Cost of Stored Energy (LCOE) and Applications to Renewable Energy Generation. *Energy Procedia*, 46, 68–77. <https://doi.org/10.1016/J.EGYPRO.2014.01.159>
- Pourebrahim, R., Tohidi, S., & Khounjahan, H. (2021). Overview of energy storage systems for wind power integration. *Energy Storage in Energy Markets*, 41–64. <https://doi.org/10.1016/B978-0-12-820095-7.00014-5>

- Putuhena, H., Sturt, F., & Gourvenec, S. (2023, July 20). *The world needs 200,000 Offshore Wind turbines by 2050: mapping the locations, constraints* - *Energy Post*. Energypost.Eu. <https://energypost.eu/the-world-needs-200000-offshore-wind-turbines-by-2050-mapping-the-locations-constraints/>
- Rahim, R., Supiyandi, S., Siahaan, A. P. U., Listyorini, T., Utomo, A. P., Triyanto, W. A., Irawan, Y., Aisyah, S., Khairani, M., Sundari, S., & Khairunnisa, K. (2018). TOPSIS Method Application for Decision Support System in Internal Control for Selecting Best Employees. *Journal of Physics: Conference Series*, 1028(1), 012052. <https://doi.org/10.1088/1742-6596/1028/1/012052>
- Raza, A., Mahmoud, M., Arif, M., & Alafnan, S. (2024). Underground hydrogen storage prospects in the Kingdom of Saudi Arabia. *Fuel*, 357, 129665. <https://doi.org/10.1016/J.FUEL.2023.129665>
- Ren, G., Liu, J., Wan, J., Guo, Y., & Yu, D. (2017). Overview of wind power intermittency: Impacts, measurements, and mitigation solutions. *Applied Energy*, 204, 47–65. <https://doi.org/10.1016/J.APENERGY.2017.06.098>
- Ritchie, H., Roser, M., & Rosado, P. (2020). CO₂ and Greenhouse Gas Emissions. In *Our World in Data*. <https://ourworldindata.org/co2/country/nigeria>
- Salee, S., & Wirasanti, P. (2018). Optimal siting and sizing of battery energy storage systems for grid-supporting in electrical distribution network. *1st International ECTI Northern Section Conference on Electrical, Electronics, Computer and Telecommunications Engineering, ECTI-NCON 2018*, 100–105. <https://doi.org/10.1109/ECTI-NCON.2018.8378290>
- Shahabuddin, M., Alim, M. A., Alam, T., Mofijur, M., Ahmed, S. F., & Perkins, G. (2021). A critical review on the development and challenges of concentrated solar power technologies. *Sustainable Energy Technologies and Assessments* 4, 47, 101434. <https://doi.org/10.1016/j.seta.2021.101434>
- Somoye, O. A. (2023). Energy crisis and renewable energy potentials in Nigeria: A review. *Renewable and Sustainable Energy Reviews*, 188, 113794. <https://doi.org/10.1016/J.RSER.2023.113794>

- Statista. (2023a). *Electricity in Nigeria - statistics & facts*. Statista. <https://www.statista.com/topics/9470/electricity-in-nigeria/>
- Statista. (2023b). *Nigeria: Unemployment rate from 2003 to 2022*. <https://www.statista.com/statistics/382366/unemployment-rate-in-nigeria/>
- Teimourian, A., Bahrami, A., Teimourian, H., Vala, M., & Huseyniklioglu, A. O. (2020). Assessment of wind energy potential in the southeastern province of Iran. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*, 42(3), 329–343. <https://doi.org/10.1080/15567036.2019.1587079>
- Ter-Gazarian, A. G. (2020). Secondary Batteries. In *Energy Storage for Power Systems (3rd Edition)* (pp. 145–162). Institution of Engineering and Technology (The IET). <https://app.knovel.com/hotlink/khtml/id:kt01294IHF/energy-storage-power/secondary-batteries>
- Torralba, V., Doblas-Reyes, F. J., Macleod, D., Christel, I., & Davis, M. (2017). Seasonal Climate Prediction: A New Source of Information for the Management of Wind Energy Resources. *Journal of Applied Meteorology and Climatology*, 56. <https://doi.org/10.1175/JAMC-D-16-0204.s1>
- Trading Economics. (2023). *Nigeria Interest Rate*. <https://tradingeconomics.com/nigeria/interest-rate>
- Transmission Company of Nigeria. (2023). *Grid Map for Existing Transmission and Generation Network*. TCN. <https://www.tcn.org.ng/repository/maps/GRID%20MAP%20FOR%20EXISTING%20TRANSMISSION%20AND%20GENERATION%20NETWORK.pdf>
- Uddin, Z., & Sadiq, N. (2023). Method of Quartile for Determination of Weibull Parameters and Assessment of Wind Potential. *Kuwait Journal of Science*, 50(3A), 105–119. <https://doi.org/10.48129/KJS.20357>
- Udoakah, Y. N., & Ikafia, U. S. (2017). Determination of Weibull Parameters and analysis of wind power potential in coastal and non-coastal sites in Akwa Ibom state. *Nigerian Journal of Technology*, 36(3), 923–929. <https://doi.org/10.4314/NJT.V36I3.36>

- U.S. Department of Energy. (2024). Federal offshore wind strategy. Retrieved from https://www.energy.gov/sites/default/files/2024-04/DOE-BOEM-Fed-Offshore-wind-v3_w150.updated.pdf
- Vallejo-Díaz, A., Herrera-Moya, I., Fernández-Bonilla, A., & Pereyra-Mariñez, C. (2022). *Wind energy potential assessment of selected locations at two major cities in the Dominican Republic, toward energy matrix decarbonization, with resilience approach*. <https://doi.org/10.1016/j.tsep.2022.101313>
- Virtanen, E. A., Lappalainen, J., Nurmi, M., Viitasalo, M., Tikanmäki, M., Heinonen, J., Atlaskin, E., Kallasvuo, M., Tikkanen, H., & Moilanen, A. (2022). Balancing profitability of energy production, societal impacts and biodiversity in offshore wind farm design. *Renewable and Sustainable Energy Reviews*, 158, 112087. <https://doi.org/10.1016/J.RSER.2022.112087>
- Wang, F. K., Amogne, Z. E., Chou, J. H., & Tseng, C. (2022). Online remaining useful life prediction of lithium-ion batteries using bidirectional long short-term memory with attention mechanism. *Energy*, 254, 124344. <https://doi.org/10.1016/J.ENERGY.2022.124344>
- Wang, L., Wang, B., Cen, W., Xu, R., Huang, Y., Zhang, X., Han, Y., & Zhang, Y. (2024). Ecological impacts of the expansion of offshore wind farms on trophic level species of marine food chain. *Journal of Environmental Sciences*, 139, 226–244. <https://doi.org/10.1016/j.jes.2023.05.002>
- WFO-Global. (2022). Financing offshore wind: Structures and risks. Retrieved from https://wfo-global.org/wp-content/uploads/2022/09/WFO_FinancingOffshoreWind_2022.pdf
- Williamson, Andrew., Lawrence, Alasdair., Short, Rebecca., Grey, Cathy., New South Wales. Department of Energy, U., & Sustainable Energy Development Authority. (2002). *NSW wind energy handbook*. Sustainable Energy Development Authority.
- Wind turbine Models. (2023). *Siemens Gamesa SG 2.1-114*. <https://en.wind-turbine-models.com/turbines/1890-siemens-gamesa-sg-2.1-114>

- Wu, J., Wang, J., & Chi, D. (2013). Wind energy potential assessment for the site of Inner Mongolia in China. *Renewable and Sustainable Energy Reviews*, 21, 215–228. <https://doi.org/10.1016/J.RSER.2012.12.060>
- Yang, L., Liao, K., Ma, Q., Ma, G., & Sun, H. (2023). Investigation of wake characteristics of floating offshore wind turbine with control strategy using actuator curve embedding method. *Renewable Energy*, 218, 119255. <https://doi.org/10.1016/J.RENENE.2023.119255>
- Yi, T., Ye, H., Li, Q., Zhang, C., Ren, W., & Tao, Z. (2022). Energy storage capacity optimization of wind-energy storage hybrid power plant based on dynamic control strategy. *Journal of Energy Storage*, 55, 105372. <https://doi.org/10.1016/J.EST.2022.105372>
- Zhao Bo, W. C. Z. X. (2018). Energy Storage Technology. In *Grid-Integrated and Standalone Photovoltaic Distributed Generation Systems - Analysis, Design, and Control* (pp. 227–241). John Wiley & Sons. <https://app.knovel.com/hotlink/khtml/id:kt011I5GG9/grid-integrated-standalone/energy-storage-technology>
- Zhou, S., Li, C., Xiao, Y., Wang, X., Xiang, W., & Sun, Q. (2023). Evaluation of floating wind turbine substructure designs by using long-term dynamic optimization. *Applied Energy*, 352, 121941. <https://doi.org/10.1016/J.APENERGY.2023.121941>
- Zivar, D., Kumar, S., & Foroozesh, J. (2020). *Underground hydrogen storage: A comprehensive review*. <https://doi.org/10.1016/j.ijhydene.2020.08.138>