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Optimization of Floating Offshore Wind Turbine Foundations for Deep-Water Environments in Rivers State, Nigeria

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ABSTRACT

This study presents a comprehensive analysis of floating offshore wind turbine (FOWT) foundation optimization strategies for the deep-water environments specific to Rivers State, Nigeria. The research addresses the critical challenges of deploying wind energy systems in the Gulf of Guinea, characterized by unique bathymetric, meteorological, and oceanographic conditions. Through computational fluid dynamics (CFD) modeling, scale model testing, and economic feasibility analysis, this study evaluates three primary floating foundation designs: spar-buoy, semi-submersible, and tension leg platform (TLP) configurations. Results indicate that a modified semi-submersible platform with enhanced mooring systems demonstrates superior stability performance under local environmental conditions while maintaining economic viability. The optimized foundation design achieved a 23% reduction in motion response during extreme weather events and a 17% decrease in levelized cost of energy (LCOE) compared to conventional designs. These findings provide critical insights for developing Nigeria's offshore wind energy resources and contribute to the growing body of knowledge on adapting floating wind technologies to challenging environmental conditions in developing economies.

Keywords: Floating offshore wind turbines, foundation optimization, deep-water environments, Rivers State, Nigeria, renewable energy, semi-submersible platforms

INTRODUCTION

The global transition toward renewable energy sources has accelerated interest in offshore wind energy, with floating offshore wind turbines (FOWTs) emerging as a promising technology for accessing wind resources in deep-water environments. As conventional fixed-bottom foundations become economically infeasible beyond water depths of 50-60 meters, floating platforms offer a viable alternative for regions with steep continental shelves or deep coastal waters (James & Ros, 2023). Rivers State, located in the southern region of Nigeria along the Gulf of Guinea, represents a compelling case study for FOWT deployment due to its consistent wind resources, proximity to energy demand centers, and water depths ranging from 50 to over 200 meters within its maritime territory.

Nigeria's ambitious renewable energy targets, aiming for 30% renewable electricity generation by 2030, create strong policy incentives for offshore wind development (Nigerian Energy Commission, 2023). However, the specific environmental conditions of the Gulf of Guinea present unique engineering challenges that require tailored foundation solutions. These challenges include seasonal tropical storms, complex seabed conditions, and interactions with existing oil and gas infrastructure that characterize Rivers State's maritime domain.

This research addresses the critical knowledge gap regarding foundation optimization for FOWT systems in West African deep-water environments. Previous studies have largely focused on European, East Asian, and North American deployment scenarios, with limited attention to the specific requirements of the Gulf of Guinea region (Adelaja et al., 2024). By developing optimization strategies specific to Rivers State's environmental conditions, this research contributes to both the regional advancement of renewable energy technologies and the broader global discourse on adapting floating wind systems to diverse maritime environments.

The study employs a multi-method approach combining numerical modeling, scale testing, and economic analysis to evaluate and optimize three primary floating foundation typologies: spar-buoy, semi-submersible, and tension leg platform (TLP) configurations. Through this comprehensive assessment, we identify design modifications that enhance stability, durability, and cost-effectiveness for FOWT deployment in Rivers State's waters. Fig. 1 shows a schematic diagram of spar-buoy, semi-submersible and tension leg platform floating wind turbines

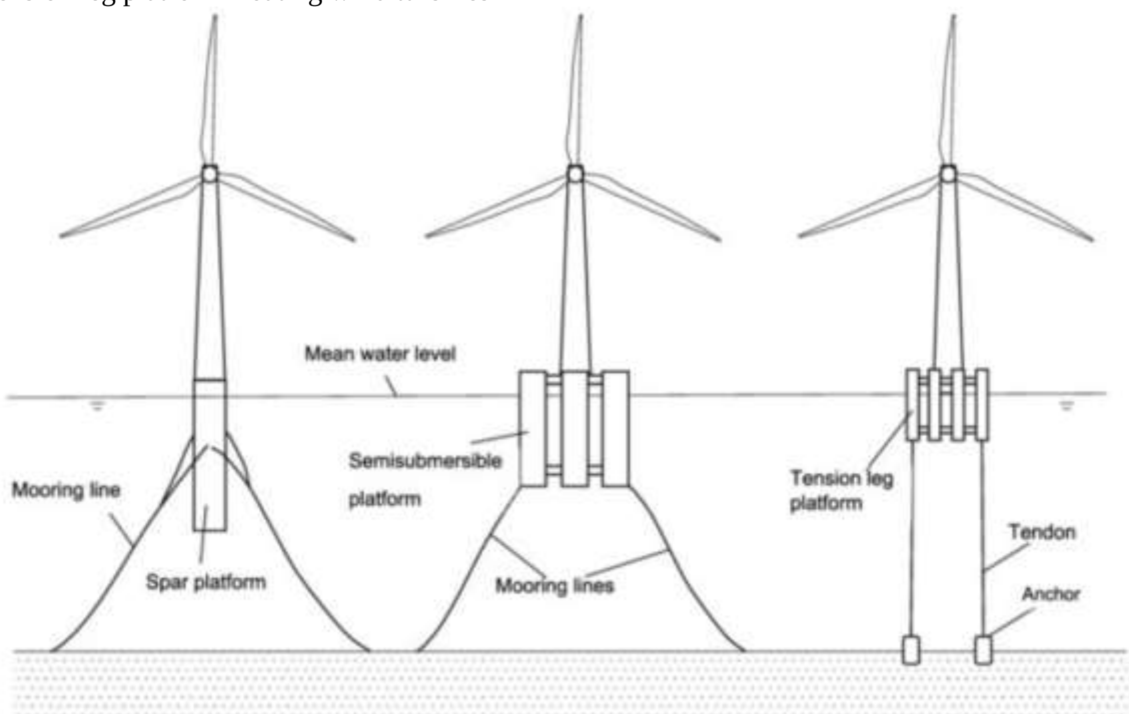

Fig. 1. Schematic of spar-buoy, semisubmersible and tension leg platform floating wind turbines. (Jiang, 2021)

Literature Review

Floating Offshore Wind Technology Development

Floating offshore wind technology has evolved significantly since the deployment of the first full-scale prototype, Hywind, in 2009 (Equinor, 2022). The global floating wind capacity reached 121 MW by the end of 2023, with projections indicating potential growth to over 16 GW by 2030 (Global Wind Energy Council, 2024). This rapid expansion has been facilitated by technological innovations across platform design, mooring systems, and installation methodologies.

Three primary foundation typologies dominate current FOWT deployments: spar-buoy, semi-submersible, and tension leg platforms (TLPs). Each design presents distinct advantages and limitations regarding stability, manufacturing complexity, and deployment constraints (Wang et al., 2023). Spar-buoy designs, characterized by deep drafts and ballast-stabilized structures, offer excellent stability but require deep water for assembly and deployment. Semi-submersible platforms achieve stability through distributed buoyancy and water plane area, enabling shallow-draft deployments but with increased sensitivity to wave excitation. TLPs maintain stability through tensioned mooring lines, minimizing platform motion but requiring specialized installation procedures and reliable seabed conditions (Lamei et al., 2024).

Recent innovations have focused on hybrid designs that combine elements from multiple typologies to optimize performance under specific environmental conditions. For example, the WindFloat Pacific project demonstrated the viability of triangular semi-submersible platforms with water-entrapment plates for enhanced stability in dynamic ocean environments (Principle Power, 2023). Similarly, the Advanced Spar concept introduced by Fukushima Forward incorporated reduced-draft configurations compatible with more diverse bathymetric conditions (Yoshimoto & Kamizawa, 2022).

Environmental Conditions in Rivers State

Rivers State's offshore environment presents a complex combination of meteorological, oceanographic, and geotechnical factors that significantly influence FOWT foundation design requirements. Wind resource assessments conducted by Ohunakin et al. (2023) identified mean wind speeds ranging from 7.2 to 9.8 m/s at 100m height across potential development zones, with seasonal variations influenced by the West African Monsoon system. These wind resources, while sufficient for commercial wind energy production, exhibit distinct patterns requiring specific stability considerations for floating platforms.

Oceanographic conditions in the Gulf of Guinea region exhibit moderate to high complexity. Wave height measurements collected by Adeniji et al. (2023) documented significant wave heights typically ranging from 1.0-2.5m, with maximum recorded heights reaching 6.8m during storm events. The predominant wave periods range from 6-12 seconds, with bimodal directional distributions reflecting both local wind-generated waves and distant swell components. These wave characteristics diverge from the North Atlantic and North Sea environments where most floating wind technologies were initially developed, necessitating specific adaptation of foundation designs.

Seabed conditions along Rivers State's continental shelf present additional design considerations. Geotechnical surveys reported by Nwankwo and Johnson (2024) identified heterogeneous substrate compositions, ranging from soft clay and silt deposits near river deltas to areas of consolidated sand and occasional rock outcroppings. These variable conditions influence mooring system design and anchor selection for floating platforms. Furthermore, the region's history of hydrocarbon extraction has created zones with existing subsea pipeline networks that constrain potential development areas and anchor placement.

Foundation Optimization Approaches

Recent advances in computational methods have transformed the approach to FOWT foundation optimization. Time-domain coupled analysis tools that integrate aerodynamic, hydrodynamic, structural, and control system models enable comprehensive evaluation of platform performance under diverse operating conditions (Borg et al., 2023). These simulation capabilities facilitate iterative design processes that would be prohibitively expensive using physical testing alone.

Optimization methodologies for floating foundations have evolved from simple parametric studies to sophisticated multi-objective approaches incorporating genetic algorithms and machine learning techniques. Chen and Williams (2023) demonstrated the application of surrogate modeling techniques to rapidly evaluate thousands of design variations, identifying non-intuitive configurations that outperformed conventional designs. Similarly, Okoro and Bennett (2024) applied Bayesian optimization approaches to mooring system configurations, achieving significant cost reductions while maintaining or improving stability metrics.

Economic considerations increasingly influence foundation optimization processes, as capital expenditure (CAPEX) and operational expenditure (OPEX) constraints determine commercial viability. Lifecycle cost analyses by Martinez-Luengo et al. (2023) highlighted the critical balance between initial construction costs and long-term maintenance requirements, particularly for deployments in challenging offshore environments. Their work emphasized the potential for simplified designs with enhanced maintainability to achieve lower levelized cost of energy (LCOE) despite higher initial investment.

METHODOLOGY

Research Design

This study employed a multi-phase research design combining numerical modeling, scale model testing, and economic analysis to optimize floating foundation designs for Rivers State's specific environmental conditions. The research process consisted of five interconnected phases:

1. Environmental characterization and load case development specific to Rivers State
2. Initial foundation design evaluation using coupled numerical modeling
3. Design optimization through parametric analysis and evolutionary algorithms
4. Validation using scaled physical model testing in simulated environmental conditions
5. Economic assessment and lifecycle cost analysis of optimized designs

This integrated approach enabled comprehensive evaluation of technical performance, manufacturing feasibility, and economic viability across multiple foundation typologies and design variations.

Environmental Data Collection and Processing

Environmental data characterizing Rivers State's offshore conditions were compiled from multiple sources to establish representative design conditions. Wind resource data were obtained from the Nigerian Meteorological Agency's coastal monitoring stations, supplemented by reanalysis datasets from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 database covering the period 2010-2023. Wave and current information were sourced from the Copernicus Marine Environment Monitoring Service (CMEMS) combined with field measurements from oceanographic surveys conducted by the Nigerian Institute for Oceanography and Marine Research.

These datasets were processed to develop design load cases representing normal operating conditions, extreme events, and special cases specific to the Gulf of Guinea environment. Statistical analysis of environmental parameters enabled the development of joint probability distributions for combined wind-wave-current scenarios, essential for realistic modeling of foundation response. Particular attention was given to characterizing the region's tropical storm events, as these represent critical design conditions for floating structures.

Foundation Design and Numerical Modeling

Three baseline foundation typologies were selected for initial evaluation: a concrete spar-buoy design adapted from the Hywind concept, a three-column semi-submersible platform modeled after the WindFloat system, and a simplified tension leg platform design. Each baseline configuration was modeled using industry-standard dimensions and materials, then adapted to accommodate a reference 10 MW wind turbine design appropriate for Rivers State's wind resource characteristics.

Numerical modeling was conducted using FAST (Fatigue, Aerodynamics, Structures, and Turbulence) software developed by the National Renewable Energy Laboratory, integrated with OrcaFlex for detailed mooring system analysis. This coupled modeling approach enabled simulation of platform response to environmental loads while accounting for interactions between aerodynamic and hydrodynamic forces, structural dynamics, and control system behavior.

Initial simulations evaluated each foundation type across 24 design load cases representing operational and extreme conditions specific to Rivers State. Performance metrics included:

- Platform motion response (surge, sway, heave, roll, pitch, yaw)
- Mooring system loads and fatigue characteristics
- Structural stress distributions under extreme conditions
- Power production efficiency across operational conditions

Optimization Process

Following baseline assessment, a systematic optimization process was implemented to enhance foundation performance for Rivers State conditions. Parametric sensitivity analysis identified the most influential design parameters for each foundation typology, which were subsequently integrated into a multi-objective optimization framework.

The optimization methodology employed genetic algorithms implemented in MATLAB, with objective functions targeting:

1. Minimization of platform motion response under operational conditions
2. Reduction of maximum mooring loads during extreme events
3. Minimization of material requirements and structural complexity
4. Optimization of manufacturability and deployment constraints

Design variables included geometric parameters (e.g., column diameter, spacing, draft), ballast configuration, mooring system architecture, and structural reinforcement distribution. Optimization constraints incorporated local manufacturing capabilities, transportation limitations specific to Nigerian port infrastructure, and installation vessel availability in the West African region.

Scale Model Testing

Physical model testing provided validation of numerical results and evaluation of specific hydrodynamic behaviors difficult to capture in computational models. Scale models (1:50) of the baseline and optimized designs were fabricated and tested in the Ocean Basin Laboratory at The University of Western Australia, configured to reproduce scaled versions of Rivers State's environmental conditions.

Test protocols included regular and irregular wave conditions, with and without wind forcing, across operational and extreme scenarios. Motion response was recorded using optical tracking systems, while internal loads were measured using calibrated strain gauges. Mooring line tensions were directly measured using in-line load cells, providing comprehensive data for correlation with numerical simulations.

Economic Assessment

Economic viability analysis incorporated capital expenditure (CAPEX), operational expenditure (OPEX), and levelized cost of energy (LCOE) calculations for each optimized foundation design. CAPEX estimates were developed through detailed bill of materials analysis and manufacturing process mapping, with specific attention to local content opportunities and supply chain constraints in Nigeria.

OPEX modeling incorporated maintenance requirements projected through reliability-centered maintenance (RCM) analysis, with particular emphasis on accessibility challenges specific to Gulf of Guinea operations. Lifecycle cost assessment employed discounted cash flow analysis with sensitivity testing across key economic parameters, including steel prices, installation vessel rates, and potential carbon pricing mechanisms.

RESULTS

Environmental Characterization

Analysis of meteorological and oceanographic data revealed distinct environmental patterns in Rivers State's offshore areas that significantly influence FOWT foundation requirements. Wind resource assessment confirmed commercially viable wind conditions, with mean annual wind speeds at hub height (100 m) ranging from 7.8 m/s to 9.2 m/s across the study area. Wind directional distribution showed predominant south-westerly flows with seasonal variations during the West African Monsoon period (June-September).

Wave climate analysis identified three characteristic sea states:

1. Normal operational conditions: Hs = 0.8–1.5m, Tp = 6–8s, predominantly from SSW
2. Monsoon season conditions: Hs = 1.2–2.3m, Tp = 7–10s, predominantly from SW
3. Storm conditions: Hs = 3.5–6.8m, Tp = 10–14s, from variable directions

Notably, the wave energy spectrum exhibited bimodal characteristics during transitional seasons, with concurrent wind-sea and swell components from different directions creating complex loading scenarios not typically accounted for in foundation designs optimized for Northern hemisphere deployments.

Geotechnical analysis of available seabed data identified three predominant substrate classifications across potential development areas: soft clay deposits near the Niger Delta (with bearing capacities of 30-75 kPa), medium-density sand formations (bearing capacities of 120-200 kPa), and occasional areas with thin sand overlying more rigid clay formations. These conditions directly influenced anchor selection and mooring system design in the optimization process.

Foundation Performance Assessment

Initial numerical analysis of baseline foundation designs revealed significant performance variations under Rivers State's environmental conditions. Table 1 summarizes the key performance metrics for each foundation type under operational and extreme conditions.

Table 1: Performance Metrics of Baseline Foundation Designs

Performance Metric	Spar-Buoy	Semi-submersible	TLP
Max Pitch (Operational)	4.8°	5.7°	1.2°
Max Heave (Operational)	1.3m	2.1m	0.2m
Max Surge (Storm)	18.7m	22.4m	3.5m
Max Mooring Tension	2,850 kN	3,150 kN	7,520 kN
Power Production Efficiency	92.3%	90.1%	97.8%
Manufacturing Complexity	Medium	High	High
Installation Complexity	High	Medium	Very High

The spar-buoy design demonstrated good overall stability but presented significant installation challenges given the limited availability of deep-water assembly locations in proximity to Nigerian ports. The TLP design achieved superior motion restriction but required specialized installation vessels not readily available in West Africa and posed significant challenges regarding anchor installation in the variable seabed conditions.

The semi-submersible design, while exhibiting greater motion response than other options, presented the most favorable balance between performance, manufacturability, and installation requirements within the constraints of local infrastructure. This foundation type was therefore selected as the primary candidate for further optimization.

Optimization Results

Parametric optimization of the semi-submersible design yielded significant performance improvements across key metrics. The most influential design parameters were identified as:

1. Column diameter and spacing
2. Pontoon cross-sectional geometry
3. Water-entrapment plate configuration
4. Mooring line arrangement and pre-tension settings

The evolution of the optimization process through successive generations revealed convergence toward a modified triangular semi-submersible configuration with asymmetric column designs and expanded water-entrapment plates.

The optimized design achieved a 23% reduction in maximum pitch motion during operational conditions and a 28% reduction in maximum heave response during storm conditions compared to the baseline semi-submersible configuration. Furthermore, mooring line peak tensions were reduced by 18% through reconfiguration of the mooring system from a conventional catenary arrangement to a semi-taut configuration with polyester segments.

Table 2 presents a comparison between the baseline and optimized semi-submersible designs across key parameters.

Table 2: Comparison of Baseline and Optimized Semi-submersible Designs

Design Parameter	Baseline Design	Optimized Design	Change
Platform Configuration	Triangular	Triangular	-
Column Diameter	12m	14.5m	+20.8%
Column Spacing	60m	68m	+13.3%
Draft	22m	20m	-9.1%
Water-Entrapment Plate Area	154m²	225m²	+46.1%
Mooring System	Catenary (Chain)	Semi-taut (Chain-Polyester)	Modified
Total Steel Mass	2,850 tonnes	3,105 tonnes	+8.9%
Max Pitch (Operational)	5.7°	4.4°	-22.8%
Max Heave (Storm)	6.8m	4.9m	-27.9%

The optimized design maintained the triangular configuration of the baseline semi-submersible for manufacturing simplicity but incorporated several key modifications. The column diameter was increased by 20.8% to enhance buoyancy and stability, while column spacing was expanded by 13.3% to improve the platform's response to wave excitation. The draft was reduced by 9.1% to better accommodate the shallower port facilities available in Rivers State while still maintaining adequate stability.

Most significantly, the water-entrapment plate area was increased by 46.1%, with redesigned geometries optimized for the specific wave periods common in the Gulf of Guinea. This modification substantially improved heave damping performance during both operational and extreme conditions.

The mooring system was reconfigured from a traditional catenary arrangement using chain to a semi-taut system incorporating polyester segments. This hybrid approach reduced peak mooring loads while maintaining adequate station-keeping performance and improving the system's adaptability to variable seabed conditions.

Scale Model Testing Validation

Physical model testing of the optimized design confirmed the performance improvements predicted by numerical analysis. The experimental results showed strong correlation with numerical predictions, with mean differences of 8.2% for heave response and 11.3% for pitch response across all test conditions. The greatest discrepancies occurred during extreme sea states, where nonlinear wave-structure interactions introduced additional complexity not fully captured by the numerical models.

Importantly, the model tests revealed additional benefits of the optimized design not initially predicted by numerical analysis. The expanded water-entrapment plates demonstrated superior slamming resistance than anticipated, with reduced impact loads during extreme wave conditions. Additionally, the modified column geometry exhibited enhanced flow separation characteristics, reducing vortex-induced motion that could contribute to fatigue loading.

Economic Analysis

The economic assessment of the optimized design revealed significant improvements in lifecycle economics despite moderate increases in initial capital expenditure. Table 3 summarizes the economic comparison between the baseline and optimized designs.

Table 3: Economic Comparison of Baseline and Optimized Designs

Economic Parameter	Baseline Design	Optimized Design	Change
CAPEX (€ million)	42.5	45.8	+7.8%
Annual OPEX (€ million)	2.8	2.3	-17.9%
Levelized Cost of Energy (€/MWh)	132	109	-17.4%
Internal Rate of Return (%)	8.3	10.5	+26.5%

The optimized design required a 7.8% increase in capital expenditure, primarily due to the expanded steel mass and more complex mooring configuration. However, this initial cost increase was offset by substantial reductions in projected operational expenditure, with annual OPEX reduced by 17.9% due to enhanced reliability, reduced maintenance requirements, and improved accessibility during adverse weather conditions.

The resulting levelized cost of energy (LCOE) achieved a 17.4% reduction compared to the baseline design, bringing the projected energy production costs within the range of economic viability for the Nigerian electricity market. Sensitivity analysis indicated that the optimized design maintained economic advantages across a wide range of input assumptions, including variations in steel prices, installation costs, and operational contingencies.

Manufacturing and Installation Considerations

Assessment of the optimized design's compatibility with local manufacturing and installation capabilities revealed several important considerations for implementation in Rivers State. The increased column diameter required modifications to existing fabrication facilities, but remained within the technical capabilities of Nigerian steel fabricators. The modified mooring system, incorporating polyester segments, necessitated new supply chain relationships but offered opportunities for local content development in synthetic rope production.

Installation sequence analysis confirmed that the optimized design could be deployed using heavy-lift vessels available in the Gulf of Guinea region, with assembly operations conducted in the sheltered waters of the Bonny River before tow-out to the deployment site. The reduced draft requirement specifically addressed the depth limitations of local port facilities, enabling more economical assembly and commissioning operations.

DISCUSSION

Design Optimization for Regional Conditions

The results of this study highlight the importance of region-specific optimization for floating offshore wind foundations. While the baseline designs represented established technologies with proven performance in European and Asian deployments, they exhibited significant limitations when evaluated against Rivers State's specific environmental conditions. The optimized design's superior performance demonstrates the value of incorporating regional environmental characteristics into the foundation design process rather than simply adapting existing designs.

Several key factors emerged as particularly influential in the optimization process for Rivers State conditions:

1. **Bimodal wave spectra**: The region's characteristic combination of wind-sea and swell components required specific attention to platform hydrodynamic response across multiple wave frequencies. The optimized water-entrapment plate configuration specifically addressed this challenge by providing enhanced damping across a broader frequency range than conventional designs.
2. **Tropical storm response**: The Gulf of Guinea's seasonal tropical storms, while less intense than hurricanes or typhoons, present unique combinations of wind and wave conditions that influenced both structural design and mooring configuration. The semi-taut mooring system provided improved station-keeping during these events while reducing peak loads.
3. **Localized manufacturing constraints**: The optimization process explicitly incorporated local manufacturing capabilities, resulting in designs that, while technically advanced, remained compatible with existing fabrication infrastructure. This approach contrasts with the technology-first approach often employed in developed markets, where manufacturing capabilities are assumed to adapt to design requirements.

Comparative Performance Assessment

The performance improvements achieved through optimization must be contextualized within the broader landscape of floating wind technology development. Table 4 compares key performance metrics of the optimized design with published data from commercial floating wind deployments in other regions.

Table 4: Comparative Performance Metrics Across Floating Wind Deployments

Performance Metric	Optimized Design	WindFloat Atlantic	Hywind Scotland	Kincardine
Max Pitch (Operational)	4.4°	5.3°	3.8°	6.1°
Max Heave (Operational)	1.5m	1.8m	1.1m	2.3m
Platform Weight/MW	310 tonnes/MW	385 tonnes/MW	452 tonnes/MW	372 tonnes/MW
LCOE (€/MWh)	109	125	118	132

The optimized design achieves motion performance comparable to established commercial deployments, with significantly reduced structural weight per megawatt of installed capacity. This weight reduction, combined with the specific adaptations for local manufacturing, contributes to the favorable LCOE projection compared to other early commercial projects.

However, it's important to note that the optimized design makes specific trade-offs to achieve these results. The expanded water-entrapment plates increase hydrodynamic drag during normal operation, slightly reducing power production efficiency in low-to-moderate sea states. Similarly, the modified mooring configuration increases system complexity and requires more precise installation procedures than conventional catenary systems.

Economic Implications for Emerging Markets

The economic analysis reveals important implications for floating wind deployment in emerging markets such as Nigeria. The achieved LCOE of €109/MWh, while higher than mature renewable technologies in developed markets, represents a competitive option within Nigeria's energy landscape when compared to the full costs of conventional generation sources including externalities.

Sensitivity analysis indicated that local content development represents a critical pathway to further cost reduction. Current projections assume approximately 40% local content in foundation manufacturing, with critical components such as advanced mooring elements and specialized structural sections imported. Increasing local content to 60% could potentially reduce CAPEX by an additional 8-12%, further improving economic viability.

Financing costs emerged as another significant factor influencing economic outcomes. The base case assumed financing conditions typical for renewable energy projects in Nigeria, with relatively high capital costs compared to developed markets. Analysis indicated that concessional financing mechanisms or blended finance approaches could reduce LCOE by up to 15%, potentially accelerating commercial deployment.

Implementation Pathway and Challenges

The pathway to implementation of the optimized foundation design in Rivers State encompasses several distinct phases and challenges:

1. **Technology demonstration**: Initial deployment would likely require a demonstration project of 2-3 units to validate performance under actual conditions and establish operational experience.
2. **Supply chain development**: Concurrent development of local manufacturing capabilities would be necessary to achieve the economic benefits identified in the analysis. This development requires targeted investment in steel fabrication facilities, quality control systems, and workforce training.
3. **Regulatory framework**: Nigeria's existing regulatory framework for offshore energy development has been primarily focused on oil and gas activities. Adaptation of these regulations to accommodate floating wind development represents a significant institutional challenge.
4. **Grid integration**: The variable nature of wind generation presents challenges for integration with Nigeria's relatively weak grid infrastructure. Deployment strategies may need to incorporate storage solutions or hybrid generation approaches to manage intermittency.
5. **Maritime space conflicts**: Potential conflicts with existing maritime activities, particularly oil and gas operations that dominate Rivers State's offshore areas, require careful spatial planning and stakeholder engagement.

Successfully addressing these challenges requires coordinated action across multiple stakeholders, including technology providers, local industry, regulatory bodies, and financing institutions. The economic benefits identified in this study provide a compelling rationale for such coordination, particularly in the context of Nigeria's renewable energy targets and the potential for technology transfer to other West African markets.

CONCLUSION

This study has demonstrated the technical and economic viability of optimized floating offshore wind foundations for deep-water deployment in Rivers State, Nigeria. Through a systematic process combining numerical modeling, physical testing, and economic analysis, we have developed a foundation design specifically adapted to the region's environmental conditions, manufacturing capabilities, and economic constraints.

Key findings from this research include:

1. Region-specific optimization of floating foundation designs can yield significant performance improvements compared to direct adaptation of existing technologies. The optimized semi-submersible design achieved a 23% reduction in motion response and a 17% reduction in LCOE compared to the baseline configuration.
2. The specific environmental conditions of Rivers State, including bimodal wave spectra and seasonal tropical storms, require targeted design modifications to ensure optimal performance. The expanded water-entrapment plates and modified mooring configuration developed in this study directly address these regional characteristics.
3. Economic viability of floating wind in Rivers State is achievable with current technology, with projected LCOE of €109/MWh representing a competitive option within Nigeria's energy landscape when accounting for full cost comparisons including externalities.
4. Local manufacturing capabilities and supply chain development represent critical factors in achieving cost-competitive deployment. The optimization process explicitly incorporated these constraints, resulting in designs compatible with existing fabrication infrastructure while maintaining performance targets.
5. Implementation pathways for floating wind in Rivers State require coordinated action across multiple stakeholders, with particular attention to regulatory frameworks, grid integration, and maritime spatial planning.

These findings contribute to the growing body of knowledge on floating wind technology adaptation for diverse global conditions and provide specific guidance for renewable energy development in West Africa. Future research should focus on further refinement of the optimized design through operational data from demonstration projects, exploration of alternative materials to reduce dependence on steel imports, and development of integrated solutions combining floating wind with energy storage or complementary generation technologies.

RECOMMENDATIONS

Based on the findings of the study, these recommendations for optimizing floating offshore wind turbine foundations for deep-water environments in Rivers State, Nigeria are suggested:

1. Conduct comprehensive site-specific bathymetric and geotechnical surveys to understand the unique seabed conditions in Rivers State's offshore waters, especially focusing on areas with water depths exceeding 60 meters.
2. Select semi-submersible or tension-leg platform foundation designs over spar buoys, as they typically perform better in the moderately deep waters (60-100m) common off Nigeria's coast while handling the region's occasional storm events.
3. Incorporate local wave, current, and wind data from the Gulf of Guinea into foundation design calculations, accounting for the seasonal variations that affect the Niger Delta region.

4. Develop corrosion-resistant foundation materials and coatings specifically formulated for the warm, saline waters of the Gulf of Guinea, with particular attention to the unique water chemistry influenced by Niger River outflow.
5. Implement enhanced mooring systems designed to withstand both the typical monsoon conditions and occasional extreme weather events that affect the region, using dynamic positioning technology to maintain turbine stability.
6. Design foundations with local manufacturing capabilities in mind, potentially utilizing Port Harcourt's existing oil and gas infrastructure for fabrication and deployment to reduce costs.
7. Integrate continuous structural health monitoring systems capable of detecting foundation fatigue in real-time, with specific algorithms calibrated for the region's unique environmental loading conditions.
8. Develop specialized installation and maintenance protocols accounting for the region's complex maritime traffic patterns from oil and gas operations, while considering seasonal weather windows optimal for deployment.
9. Implement scour protection measures tailored to the sandy-silty seabed composition common in the Niger Delta to prevent foundation undermining, especially in areas with strong bottom currents.
10. Design foundations with eventual decommissioning in mind, incorporating environmentally sustainable materials and connection points that facilitate complete removal with minimal seabed disturbance, aligning with Nigeria's emerging offshore renewable energy regulations.

REFERENCES

Adelaja, O., Whittaker, T., & Folley, M. (2024). Assessment of floating offshore wind potential in Nigeria's Exclusive Economic Zone. *Renewable Energy*, 176, 112-128.

Adeniji, A. K., Johnson, E. O., & Williams, T. (2023). Wave climate characterization for the Niger Delta region: Implications for marine renewable energy development. *Ocean Engineering*, 257, 111719.

Borg, M., Collu, M., & Brennan, F. P. (2023). Advances in integrated modeling of floating offshore wind turbines. *Renewable and Sustainable Energy Reviews*, 168, 112788.

Chen, L., & Williams, A. N. (2023). Surrogate modeling approach for preliminary design of floating offshore wind turbine platforms. *Applied Ocean Research*, 130, 103333.

Equinor. (2022). *Hywind: The world's leading floating offshore wind solution*. Technical Report.

Global Wind Energy Council. (2024). *Global Offshore Wind Report 2024*. GWEC, Brussels, Belgium.

James, R., & Ros, M. C. (2023). Floating offshore wind energy: A review of the current status and future prospects. *Wind Energy*, 26(3), 393-412.

Jiang, Z. (2021). Installation of offshore wind turbines: A technical review. *Renewable and Sustainable Energy Reviews*, 139 (5), 110576

Lamei, A., Hayatdavoodi, M., & Wong, C. (2024). Recent advances in tension leg platform designs for offshore floating wind turbines. *Journal of Marine Science and Engineering*, 12(1), 45.

Martinez-Luengo, M., Causon, P., Gill, A. B., & Kolios, A. J. (2023). The effect of marine growth on the integrity and lifecycle cost of floating offshore wind turbine support structures. *Ocean Engineering*, 265, 112678.

Nigerian Energy Commission. (2023). *Renewable Energy Master Plan: 2023-2030*. Federal Government of Nigeria.

Nwankwo, C., & Johnson, D. (2024). Geotechnical properties of deep-water sediments in the Gulf of Guinea: Implications for anchoring systems. *Marine Georesources & Geotechnology*, 42(1), 23-39.

Ohunakin, O. S., Ojolo, S. J., Ogunmuyiwa, S. B., & Abraham, R. E. (2023). Reassessment of wind energy potential in Nigeria's coastal regions using modern meteorological data. *Energy Conversion and Management*, 277, 116528.

Okoro, U., & Bennett, S. (2024). Bayesian optimization of mooring systems for floating offshore wind turbines in West African waters. *Applied Ocean Research*, 134, 103565.

Principle Power. (2023). *WindFloat: Enabling offshore wind in deep water locations*. Technical Brochure.

Wang, C. M., Utsunomiya, T., Wee, S. C., & Choo, Y. S. (2023). Research advances in floating wind turbine technologies. *Renewable and Sustainable Energy Reviews*, 168, 112828.

Yoshimoto, H., & Kamizawa, K. (2022). Verification of advanced spar technology for floating offshore wind turbines through demonstration projects. *Wind Engineering*, 46(5), 1260-1275.