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Tidal Energy: Accelerating Nigeria's Sustainable Energy Supply

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Abstract- The global demand for electricity, coupled with commitments to climate change mitigation, has intensified the search for sustainable and low-carbon energy alternatives. Despite Nigeria's abundant renewable energy resources, the country's electricity sector continues to experience persistent supply deficits arising from ageing infrastructure, transmission losses, and overdependence on fossil fuel-based generation. While considerable attention has been directed towards solar, wind, and hydropower, tidal energy remains largely unexplored despite Nigeria's extensive Atlantic coastline and favourable coastal hydrodynamic conditions. This study examined the potential of tidal energy as a viable renewable resource for accelerating Nigeria's sustainable electricity supply. Specifically, the study assessed the tidal energy potential along Nigeria's coastal zones, evaluated its feasibility for electricity generation, and examined its contribution to Nigeria's energy transition and sustainable development agenda. A systematic literature review and analytical synthesis approach was adopted, drawing evidence from peer-reviewed journal articles, technical reports, and policy documents obtained from recognized academic databases. The reviewed literature was analyzed thematically with emphasis on tidal resource availability, technological feasibility, environmental implications, policy readiness, and integration into the national energy mix. The findings revealed that Nigeria possesses significant tidal energy potential, particularly within the Niger Delta, Bonny River, Brass River, Forcados Estuary, Lagos Lagoon, and Calabar Estuary, where favourable tidal currents and estuarine characteristics exist. The study further established that tidal energy offers predictable electricity generation, enhances energy security, supports rural and coastal electrification, reduces dependence on fossil fuels, contributes to climate change mitigation, and advances the achievement of the Sustainable Development Goals. However, high capital investment requirements, technological limitations, inadequate research, weak policy frameworks, limited technical expertise, and grid integration challenges continue to hinder large-scale development. The study concludes that tidal energy represents a strategic component of Nigeria's future renewable energy portfolio and recommends the development of a dedicated national marine energy policy, increased investment in research and pilot projects, strengthened public-private partnerships, improved coastal resource mapping, and enhanced institutional support to facilitate its successful integration into Nigeria's sustainable energy transition.

Keywords: hydropower, tidal energy potential, fossil fuels, sustainable electricity supply renewable resources.

I. INTRODUCTION

With the backing of climate mitigation commitments and increasing global electricity demand (Adebayo et al., 2024; Chowdhury et al., 2020), the modern energy landscape is being reshaped. The countries in the Global South are also attempting to develop their industries and improve their standards of living, while struggling from energy shortages (World Bank, 2021). Developed and developing economies have made further efforts to decarbonise their energy generation and to guarantee their energy security. This has driven a continuous research for renewable energy technology (Fouz et al., 2021; Lieber et al., 2024). Marine renewable energy has become an increasingly essential choice for poor nations in their efforts to strike a balance between economic growth and environmental sustainability in this worldwide transition (Novo & Kyozuka, 2021; Oyedokun et al., 2022). The peculiarities among renewable energy resources have drawn growing scientific and policy interests in tidal energy. However, tidal energy is not impacted by atmospheric conditions that can change over time, and is more predictable for long-term electricity planning purposes (Chowdhury et al., 2020). There are also several examples of historical evidence from various coastal contexts which substantiate its technological potential. It is established that the environment within estuaries is favourable enough for high energy harvesting (Fouz et al., 2021), and that several favourable locations for harnessing tidal energy exist in estuaries in Sub-Saharan Africa (Adebayo et al., 2024). Experimental trials have also demonstrated that useful electrical generation can be achieved with very slow tidal currents, thus increasing the number of potential locations for installation of tidal energy technology (Akinshilo et al., 2026). In Asia and Europe, tidal stream technologies are showing good performance and integration into regional electrical systems (Lieber et al., 2024; Novo & Kyozuka, 2021). But with this shift towards a global trend, the imbalance of energy supply and demand continues in Nigeria. The national power sector remains structurally deficient as a significant proportion of the population still lacks sustainable access to electricity from the grid (World Bank, 2021). Despite an increase in installed capacity for power generation over the years, ageing infrastructure, transmission losses, maintenance problems, and frequent system failures (Akuru et al., 2017) hamper the effective supply of energy. The issues raised by these problems have convinced many that the country's renewable energy portfolio needs diversification from the traditional sources. While the popular energy story in Nigeria has largely been confined to solar, hydropower, biomass, and wind energy, the focus is largely missing the marine renewables (MR) resources (Nweke & Ali, 2025; Oyedokun et al., 2022). However, Nigeria's coastline to the Atlantic Ocean is a vast natural resource of renewable energy which can augment the existing systems of electricity generation (Owebor et al., 2021). There is the view of some scholars that diversification of the renewable energy mix, which comprises emerging sources of renewable energy such as tidal energy, is the key to achieving long-term national energy security, rather than the traditional renewable energies (Nweke & Ali, 2025; Owebor et al., 2021; Oyedokun et al., 2022). However, despite its potential to support the Country's blue economy and sustainable development goal (SDG), marine energy remains undervalued and unstudied and supported by institutions and scientific bodies (Nweke & Ali, 2025). This means that the potential of the tidal energy has not been optimized in Nigeria's energy transition plan particularly regarding resource assessment, techno-economic viability and integration in the national energy strategy (Adebayo et al., 2024; Nweke & Ali, 2025; Owebor et al., 2021). This information gap makes it difficult to make decisions based on evidence for renewable energy diversification and limits the country's capacity to use the coastal resources efficiently. Against this background, the present study investigates the possible contribution of tidal energy to sustainable electricity supply in Nigeria in the context of energy transition and decarbonization.

Specifically, the study seeks:

- To assess the tidal energy potential along Nigeria's coastal zones.
- To evaluate the feasibility of tidal energy for electricity generation in Nigeria.
- To examine how tidal energy can support Nigeria's sustainable energy transition and policy direction

II. CONCEPT REVIEW AND THEORETICAL FRAMEWORK

2.1 Concept of Sustainable Energy Supply

Access to reliable energy has become one of the defining prerequisites of economic growth, industrial productivity and better quality of life. But the problem for many countries today is not only to produce more electricity. It is to ensure that energy is produced and delivered in ways that are economically feasible, environmentally responsible and socially inclusive in the long term. This worry has brought the idea of sustainable energy supply into the focus of the global energy policy, especially as countries seek to minimize greenhouse gas emissions while fulfilling a growing demand for electricity. So sustainable energy supply is energy systems that can meet the present and future energy needs of the society without affecting the environment, the economic stability and the future generations to meet their energy needs (Kai et al., 2021; Khan et al., 2022; Lewis et al., 2021).

In the energy literature, sustainability of energy supply is strongly related with decarbonisation, diversification of the energy mix and the integration of renewable energy technologies such as solar, wind, hydro and marine energy systems. It also highlights

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advances in energy efficiency, reduction of transmission losses, and the strengthening of resilient energy infrastructure that can respond to variations in demand and climate pressures (Lewis et al., 2021; Khan et al., 2022).

The notion is more relevant in emerging economies like Nigeria due to the problems of energy poverty, low power generation capacity and poor transmission infrastructure. In the context, sustainable energy supply is not only an environmental desire but a development imperative. This necessitates the transition of the national energy system towards diversified, reliable and low carbon energy sources (Kai et al., 2021). Sustainability is now more and more understood as a policy-driven transformation that requires institutional reforms, technological innovation and long-term investment, and not only the adoption of cleaner technology.

2.2 Concept of Tidal Energy

Tidal energy is a type of marine renewable energy that is derived from the regular rise and fall of sea levels and the motion of tidal currents, principally driven by the gravitational interaction between the Earth, the Moon, and the Sun. By employing specifically developed engineering systems, these regular hydrodynamic cycles can be transformed into power, making tidal energy one of the few renewable resources for which a high level of prediction accuracy can be achieved (Fubara et al., 2025; Gu et al., 2024).

Unlike wind and solar, tidal energy is predictable in time and constant in operation, therefore providing a reliable source of renewable electricity for base-load and peaking power generation. Tidal energy is one of the most predictable marine renewable energy sources as its cyclic nature is controlled by astronomical influences rather than short-term meteorological events (Fubara et al., 2025). Similarly, Gu et al. (2024) highlight the strategic importance of this for coastal areas with large tidal ranges and current speeds.

The development of tidal energy technology has progressed significantly from simple mechanical tidal mills to complex grid connected plants that can sustain national electrical grids. The commercial use of the technology has been concentrated in places with favorable tides and a high level of maritime engineering capability. The technical feasibility and growing commercial importance of marine renewable energy are evidenced by notable examples such as the La Rance Tidal Power Station in France, tidal stream projects in Scotland, the Bay of Fundy in Canada, and emerging tidal energy projects in South Korea and China (Kangaji et al., 2025; Lieber et al., 2024; Novo & Kyozuka, 2021).

2.3 Classification of Tidal Energy Technologies

Tidal energy systems are broadly classified into four principal technological categories based on their operational mechanisms and site requirements.

Tidal barrages are large dam-like structures constructed across estuaries or bays with significant tidal ranges. They generate electricity by controlling the flow of seawater through sluice gates that drive turbines during both ebb and flood tides. Although highly efficient under suitable geographical conditions, tidal barrages are capital intensive and may significantly alter estuarine hydrodynamics and coastal ecosystems (Nachtane et al., 2020).

Tidal lagoons operate on similar hydraulic principles but are constructed as semi-enclosed artificial basins along coastal zones rather than across natural estuaries. They reduce some ecological disruption associated with barrages and allow greater flexibility in siting. However, high construction and maintenance costs remain a major limitation to widespread adoption (Lewis et al., 2021).

Tidal stream turbines extract kinetic energy directly from fast-moving tidal currents using submerged turbine systems analogous to underwater wind turbines. These systems are modular, scalable, and generally associated with lower environmental impact. Their efficiency, however, depends strongly on the presence of high-velocity tidal channels, which limits their geographical applicability (Khan et al., 2022).

Dynamic tidal power systems represent an emerging conceptual technology that involves constructing long dam-like structures perpendicular to coastlines to exploit phase differences in tidal propagation. Although theoretically promising for relatively straight coastal regions, the technology remains at an early developmental stage and has not yet achieved commercial deployment (Gu et al., 2024).

2.4 Positioning Tidal Energy within Renewable Energy Development
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2.5 Theoretical Framework
This study is grounded in two complementary theoretical perspectives: Sustainable Development Theory and Energy Transition Theory.

Sustainable Development Theory, as articulated in the Brundtland Report (1987), conceptualises development as a process that meets present needs without compromising the ability of future generations to meet their own needs. In energy systems, this theory provides a normative foundation for balancing environmental protection, economic growth, and social inclusion. Within the context of tidal energy, it justifies the exploration of low-carbon marine resources as part of a broader strategy to reduce greenhouse gas emissions while enhancing long-term energy security. For Nigeria, the theory is particularly relevant given the need to reconcile rising energy demand with environmental sustainability and coastal resource protection.

Energy Transition Theory explains the structural transformation of energy systems from fossil fuel dependence towards low-carbon and renewable energy configurations. It emphasises the role of technological innovation, institutional reform, policy incentives, and investment flows in driving systemic change. In developing countries, the transition process is often constrained by governance capacity, infrastructure limitations, and financial constraints, making policy design and institutional coordination critical determinants of success. In this study, Energy Transition Theory provides an analytical lens for understanding how tidal energy can be integrated into Nigeria's renewable energy portfolio as part of a gradual but structured decarbonisation pathway.

III. METHODOLOGY

This study adopts a systematic literature review and analytical synthesis approach to examine the role of tidal energy in accelerating Nigeria's sustainable energy supply. The approach enables a structured evaluation of existing scientific and policy-oriented literature on tidal energy development, marine renewable energy systems, and Nigeria's electricity sector without reliance on primary data collection. Relevant studies were identified from established academic databases, including Scopus, ScienceDirect, IEEE Xplore, and Google Scholar, using defined keywords such as tidal energy, marine renewable energy, energy transition, and Nigeria energy security. Peer-reviewed journal articles, technical reports, and policy documents published within the last two decades were included, while non-scholarly sources and non-relevant publications were excluded. The selected literature was analysed thematically, focusing on tidal resource potential, techno-economic feasibility, environmental implications, and policy readiness for integration into Nigeria's energy mix.

IV. RESULT AND DISCUSSION

4.1 Nigeria's Energy Landscape and the Need for Alternative Renewable Energy Sources

Nigeria's electricity sector continues to reflect a deep structural mismatch between energy demand, installed capacity, and actual delivered supply The population is over 200 million and the country continues to be under pressure from its power infrastructure. According to Akuru et al. (2017) the national electricity demand is approximately 31.2 GW and the installed generation capacity is 14.38 GW, with actual generation power rarely exceeding 6 GW due to inefficiencies in operation and transmission. This continued failure shows that significant fraction of installed infrastructure is not being used to produce electricity, thus the system is far from optimal efficiency. The message is that there will be a chronic lack of supply, limiting economic productivity and household energy security.

In comparison to the benchmark planning criteria by population, this shortage is more apparent. With the ratio applied in many countries of 1,000MW per million population, Nigeria needs nearly 200GW of installed capacity to cater for the country's demand. This is a theoretical need that is not being met in the current production scope, pointing to the structural nature of the energy crisis. The World Bank (2023) data also shows that generation from renewable energy sources – excluding hydro – is well below meaningful scale, which reflects limited penetration of modern renewable technologies into the national grid system. In a similar vein, while policy is dedicated to scaling-up renewable energy, the overall energy mix still consists of a limited and concentrated energy basket that continues to be susceptible to disruptions, dependence on fuels, and limitations in infrastructures, as noted by Owebor et al. (2021) and Oyedokun et al. (2022).

To address these constraints, Nigeria has been steadily championing renewable energy projects, such as those that harness solar power, and decentralised energy schemes. These are all steps towards cleaner energy routes for the grid, but they're not enough to close the gap on the growing demand for electricity. The lack of reliability of grid electricity has also led people to rely on self-generation with fossil fuel-based alternatives, which further contributes to economic inefficiency and environmental pressure, as noted by Abdullah and Adeleke (2023). Over the years, Nigeria has continued to have weak performance in electricity generation, largely due to the dominance of gas fired plants and the contribution from hydropower with some coal-based generation (Anumaka, 2012) as confirmed by other broad energy sector studies (World Energy Council, 2020). In such a context, the importance of diversifying from traditional Renewable Energy becomes more and more apparent, especially towards under-explored, but potentially stable resources that can support long-term energy security and sustainability.

4.2 Assessment of Nigeria's Coastal and Marine Tidal Energy Potential

4.2.1 Coastal and Marine Energy Geography of Nigeria

Nigeria possesses a coastline of approximately 853 km along the Gulf of Guinea, forming a continuous interface between terrestrial hydrological systems and the Atlantic Ocean. This coastal belt is not uniform in its geomorphology or energy potential; rather, it is structured into a complex system of lagoons, estuaries, distributaries, and mangrove-dominated wetlands. The spatial distribution of coastal states includes Lagos, Ogun, Ondo, Bayelsa, Rivers, Delta, Akwa Ibom, and Cross River, each contributing differently to marine hydrodynamic behaviour and tidal energy availability.

The dominant physical control of coastal energy dynamics is the Gulf of Guinea tidal regime, which influences semi-diurnal tidal oscillations and drives periodic water mass exchange along the Nigerian shoreline. However, the most significant energy concentration does not occur along open coasts but within the Niger Delta estuarine complex, where river discharge interacts with oceanic tidal forcing to produce amplified current velocities in confined channels. This interaction creates spatial gradients in kinetic energy density, particularly in distributary mouths and narrow estuarine inlets.

From a geomorphological perspective, Nigeria's coastal system is characterised by low-gradient shorelines, extensive sediment deposition, and dynamic channel migration. These conditions contribute to the formation of shallow-water environments where tidal currents are spatially accelerated due to channel constriction and bathymetric variation. The presence of mangrove forests and intertidal flats further modifies flow resistance, creating heterogeneous energy distribution patterns across short spatial scales. As noted in coastal energy systems literature, such estuarine-lagoon interfaces often represent favourable zones for marine renewable energy extraction due to their predictable hydrodynamic cycles and flow channelisation effects (Lewis et al., 2021; Gu et al., 2024).

4.2.2 Hydrodynamic Characteristics of Coastal Waters

The hydrodynamic regime of Nigeria's coastal waters exhibits complex, multi-scale variability driven by spatial, seasonal, and environmental factors. These dynamics are critical for infrastructure design, navigation, estuarine management, and the potential deployment of marine renewable energy systems.

Tidal range variability along the Nigerian coast exhibits a distinct spatial gradient, transitioning from a micro-tidal environment in the western region to a meso-tidal zone in the eastern Niger Delta and Cross River estuaries. Tides in the Atlantic Ocean offshore of Nigeria approach predominantly from the southwest and are primarily semidiurnal. While the tidal range remains approximately (1.0m) around Lagos in the west, it increases progressively eastward, reaching amplitudes between (2.0 m) and (3.0m) in the Cross River and Calabar River estuaries. This regional fluctuation dictates the extent of coastal inundation and underpins the geomorphological development of transgressive mud beaches and barrier islands.Within estuarine channels, current velocity distribution is highly heterogeneous and strongly governed by channel bathymetry, depth, and hydraulic roughness. The tidal strength is strongest at the coastal inlets and decreases progressively with distance inland. In the Qua Iboe and Cross River estuaries, average current velocities typically range from (0.5 m/s) during neap tides to over (1.0 m/s) during spring tidal cycles . In addition, current velocities in the estuary are vertically and laterally asymmetric, with higher velocities in the middle of the estuary than along the boundaries, particularly in shallower canals near the bank.

Astronomical tides and the changing river discharges with the wet and dry seasons of Nigeria appear to be important factors in the seasonal variability of tidal flow. Heavy rainfall occurs during the wet season (usually April to September) that results in significant river runoff from the land, generating a seaward residual current. This increase of fluvial discharge is a resisting force that directly opposes tidal propagation in the ocean, limiting the extent of upstream penetration by floodwaters. In turn when there are fewer fresh water inputs in the dry season, the semidiurnal tides can be much stronger, and are able to travel far further upstream, greatly influencing the hydrodynamic balance of the estuarine basins.The suspended sediment load and bed load changes of these river systems are important in determining the viability of turbines for generating tidal energy. The median sediment diameter (D50) ranges between fine to coarse sand, silts and organic clays, typical of an estuarine bed.

High sediment transport rates (high peak tidal currents in the tidal assessment period are able to mobilize fine suspended solids) can result in highly abrasive and erosive environments, particularly during ebb-dominant phases and wet seasons. This can lead to accelerated erosion of blades and

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mechanical fouling of hydrokinetic turbine equipment, requiring careful sediment management and specific maintenance practices for any proposed coastal energy resource development.

The salinity gradients and estuarine mixing dynamics are clearly spatiotemporally structured and are driven by freshwater inflow and tidal pumping. The salinity values in estuaries like the Cross River and Qua Iboe varies from (0{ ppt} in the upstream (fresh water) areas to (20{ ppt} in the areas close to the ocean inlet. Less river discharge in dry seasons leads to a vertically well-mixed or partially mixed estuarine water column, and wet seasons cause the salt wedge to be pushed further seaward with high volume freshwater outflows. These periodic shifts in water density directly influence the vertical stratification of the estuaries, affecting localized estuarine circulation and nutrient transport. Wave-current interaction effects in shallow coastal zones are a dominant feature along the Nigerian coastline, which is exposed to persistent, high-energy southwesterly swells driven by Atlantic winds. These energetic waves, often averaging 2{m) in height, interact strongly with both tidal currents and localized river outflows. In estuarine mouths, such interactions induce wave refraction, alter breaker heights, and occasionally trigger flow reversals in longshore transport such as shifts from east to west directions during ebb tides. This complex superposition of forces exacerbates coastal erosion at downdrift stations while accelerating sediment accretion in sheltered up-drift zones, profoundly modifying nearshore hydrodynamics.

4.2.3 Quantitative Estimation of Tidal Energy Potential

Due to the high hydrodynamic variability identified across the micro-tidal western zone (e.g., Lagos) and the meso-tidal eastern zone (e.g., Cross River and Calabar River estuaries), the theoretical framework must account for site-specific fluid densities, varying cross-sectional geometries, and time-dependent velocity vectors.The baseline theoretical energy calculation framework relies on the fundamental conservation of energy laws applied to fluid mechanics, adapted specifically for open-channel and estuarine environments.

Tidal Stream Kinetic Energy Formulation

The theoretical kinetic power flux ((Pk) contained within an unobstructed fluid stream moving through a designated cross-sectional area represents the maximum boundary of available power. This flux is expressed mathematically as:

$$P_K = \frac{1}{2} \rho A v3$$

Where:

P_K = Theoretical kinetic power output (Watts),

ρ = Fluid density (kg/m^{3}\)), which varies across Nigerian estuaries due to seasonal salinity and temperature (\(\rho \approx 1021 - 1026 kg/m^3

A = Cross-sectional sweep or channel area perpendicular to the flow vector (m2)

v(t) = Time-dependent, instantaneous depth-averaged tidal current velocity (m/s)

Because estuarine currents are inherently sinusoidal, the velocity is modeled as a function of time (t) over a specific tidal period (T):

$$v(t) = V_{\max} \sin\left(\frac{2\pi t}{T}\right)$$

Where V_{max} is the peak current velocity achieved during spring or neap tidal phases. Integrating this time-varying velocity yields the total theoretical energy ((Ek) available over a single semidiurnal tidal cycle:

$$E_k = \int_0^T \frac{1}{2} \rho A \left[V_{\max} \sin\left(\frac{2\pi t}{T}\right)\right]^3 dt$$

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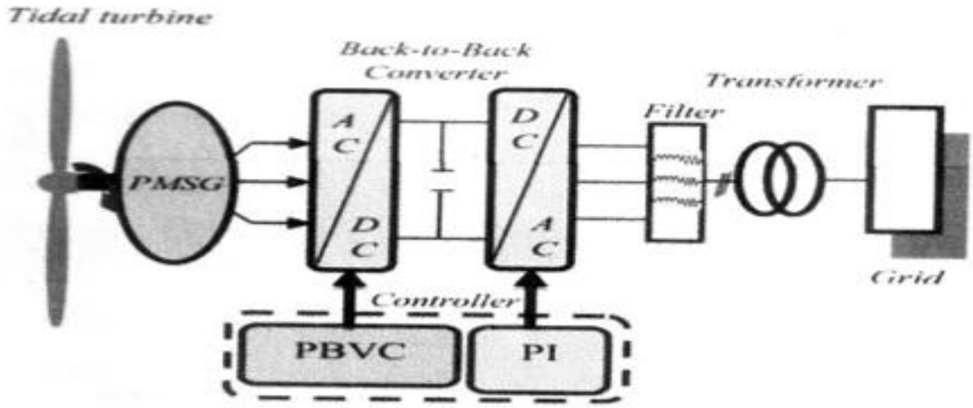

Fig.1.Tidal energy systems configuration based on a PMSG [38]

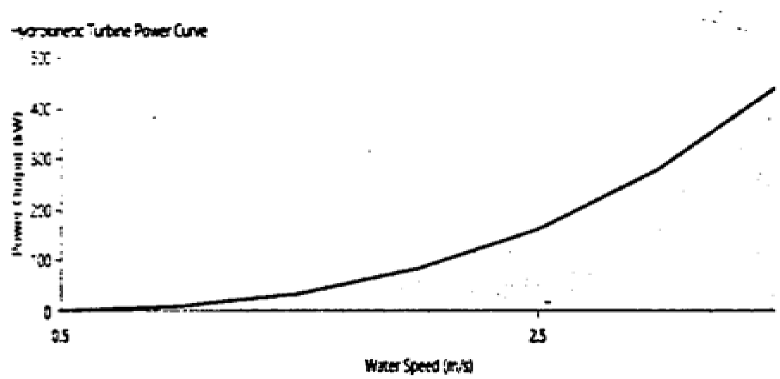

Fig.2. Tidal Output Curve For A Typical Schottel Tidal Turbine

Table 1 Tidal Parameters of a Typical Schottel 54kw Tidal Turbine

Parameters	Symbols	Values
Cut-in tidal speed	*Vcuttid*	<1 (m/s)
Rated tidal speed	*Vratedtid*	3 m/s
This Cross-Sectional area of turbine	*A*	$201.06m^2$
Power coefficient	C_p	0.44
Cut-out tidal speed	*Vcututtid*	>5m/s

The principle of tidal range systems is to create electricity by using the vertical movement of the ocean between high and low tides, which is usually done through a barrage or a lagoon structure. These systems are based on potential energy resulting from the difference in water levels and are typically found in estuarial areas where there is a substantial tidal range. Although technologically advanced, tidal range systems are still expensive and location-dependent because of site-specific needs. The design and operation of their structures and impacts have received extensive attention in the literature, especially regarding their effects on the environment and their extensive modification of the coast. Compared to other flexible technologies, tidal range technologies tend to have a long development time and high infrastructure demands, thus reducing their potential for widespread usage.

Tidal stream systems use the energy of the moving water to produce electricity by installing submerged turbines in channels of fast-moving water. Because of its modularity, low visual impact and versatility to various marine settings, the approach has grown in interest. Lewis et al (2021) present a standardised tidal-stream power curve to better estimate the resource resource and provide greater site-to-site comparability globally, which aids the analytical foundation for deployment planning. The understanding of turbine hydrodynamics and the interaction between the flow has also improved, with Lieber et al. (2024) emphasizing how the wake dynamics and turbulent flow conditions affect the efficiency of energy capture. Based on recent technological evaluations, tidal stream technology has increasingly been considered as a potential method of distributed marine energy generation in areas where strong and steady tidal currents exist (Kangaji et al., 2025).

The identification of high potential tidal energy zones follows the process outlined below:
Tidal energy hotspots are not something that can simply be determined based on geographical classification alone but rather it requires a spatial understanding of hydrodynamics. The energy potential is basically a function of channel geometry, the magnitude of the tides, the continuity of flows, and the stability of sediments.

4.3.1 Lagos Coastal System
The coastal system of Lagos is a complex lagoon–ocean interface characterized by limited inlets, which connect the Atlantic Ocean to the Lagos Lagoon, where a lagoon ocean exchange takes place. These constrictive channels create acceleration in the flow which increases the energy density in the flow. The area is also subject to high anthropogenic pressure (urbanization, port activities, pollution loads) that could lead to more energy infrastructure maintenance needs. In spite of the limitations, the system is hydrodynamically significant, with significant bidirectional tidal flushing behaviour (Akinshilo et al., 2026).

4.3.2 Bonny River System
Tidal penetration and channelised flow structure in the Bonny River system makes it one of the energetically favourable estuarine system in Nigeria. A persistent interaction flow regime between river discharge and ocean tides is established which results in relatively constant current speeds. Moreover, co-location with petroleum infrastructure also offers opportunities for grid integration and constraints of environmental risk and spatial competition. The system has high potential for energy concentration as shown within narrow distributary channels in terms of hydrodynamics (Fubara et al., 2025).

4.3.3 Brass River Basin
Brass River basin is relatively undeveloped for industrial use, and provides a more stable hydrological regime. The amplitude of the tide is moderate, and the flow patterns are relatively consistent, which facilitates the prediction of energy that can be extracted from the tide. This means that the turbines have a better chance of being sustained over extended operation periods compared to other systems in the Niger Delta region (Khan et al., 2022).

4.3.4 Forcados Estuary
Intense sediment transport processes and dynamic channel reshaping are the characteristics of the Forcados Estuary. Nevertheless, the estuary has a high capacity for flushing because of the high capacity for flow exchange in the direction of flow. This flushing behaviour increases the availability of kinetic energy, but instability in the infrastructure is a long-term engineering challenge due to sedimentation (Kai et al., 2021).

4.3.5 Calabar Estuary
The Calabar Estuary on the other hand has a narrower channel morphology that causes velocity amplification due to geometric confinement. Tidal flow further contributes to freshwater–saltwater exchange dynamics in the Cross River system, resulting in regions of higher kinetic energy density, ideal for tidal stream development (Lieber et al., 2024).

4.3.6 Niger Delta Coastal Belt (Integrated Zone)
The Niger Delta coastal belt is the biggest tidal interaction zone in Nigeria. It has a multi-channel estuarine structure that produces a number of micro-sites of energy concentrations that are related to the local bathymetry and channel geometry.. Collectively, this region offers the highest cumulative tidal stream energy potential due to spatial aggregation effects and persistent tidal forcing (Novo and Kyozuka, 2021).

V. CONTRIBUTIONS OF TIDAL ENERGY TO NIGERIA'S SUSTAINABLE ENERGY SUPPLY

Tidal energy is one of the untapped renewable energy resources in Nigeria. While the focus on national discussions has been solar, wind and hydropower, the potential of marine energy resources is not as extensively explored given Nigeria's long Atlantic coastline. The introduction of this new technology into the national energy mix offers both a technical solution and a strategic approach to achieving long-term energy diversification and sustainability. In a systems context, the potential of tidal energy is complementary to other intermittent renewable energy resources, such as solar and wind energy, helping to achieve energy transition goals. Tidal cycles are more predictable than solar irradiance or wind speed, are geographically stable, and provide a reliable renewable baseload that can help make the grid more predictable. Marine renewable systems have also gained attention in the broader literature on energy transitions in developing economies as stabilising elements in diversified energy portfolios, especially in coastal areas where the potential for resource complementarities can be realised (Rodríguez-Pérez et al., 2023; Samsó et al., 2023).

5.1 Enhance the electricity generation capacity

Nigeria is still having an on-going power deficit as the installed generation capacity and demand are not on par. This deficiency is exacerbated by transmission losses, infrastructure limitations, and relying too heavily on the thermal generation sources. In this context, tidal energy is a technically viable renewable energy source that has the potential to contribute to the nation's overall generation capacity. Tidal systems are highly predictable systems, as opposed to some renewable sources that change over time. The predictability makes tidal power an attractive alternative for hydropower and gas fired power plants, especially in coastal states where demand hubs are within the marine resources. The findings from empirical studies indicate that coupling tidal technologies with coastal energy systems has the potential to increase installed capacity and stabilize energy supply while minimizing energy fluctuations (Adebayo et al., 2024; Victor et al., 2025). The kinetic energy flows of the tidal streams in Niger Delta region of Nigeria are consistent and if well harnessed using modern turbine systems could give a meaningful contribution to distributed generation. This is especially true where grid extension is economically and technically limited.

5.2 Enhancing Energy Security

Structurally, Nigeria's energy security is limited by its dependence on fossil fuels, especially natural gas; and its vulnerability to global price fluctuations and domestic supply shortages. Tidal energy is also a way to increase energy security and shift away from greater reliance on fossil fuels and market volatility. Tidal energy is locally available, renewable and inexhaustible, which helps to reduce dependence on imported fuels and external supply chains. This decentralisation of energy generation helps to increase energy autonomy and energy resilience. Diversification of energy sources is one of the main pillars of long-term energy security for developing economies, especially for the structural transitions in progress in those economies, as noted by Owebor et al. (2021). Also, tidal energy systems may be deployed as decentralised assets in coastal energy hubs to lessen stress on central generation assets and promote redundancy in the national grid system.

5.3 Supporting Rural and Coastal Electrification

High cost of infrastructure and challenging geographical conditions have prevented a large percentage of coastal and riverine communities in Nigeria from having access to electricity. The extension of national grid infrastructure services is often not cost-effective and therefore energy poverty persists in these regions. Tidal energy is a decentralised solution, which is especially appropriate for off-grid and mini-grid applications. Small and medium scale tidal installations can generate a reliable source of electricity for fishing communities, cold storage facilities, water treatment plants and small businesses. This localized generation model helps decrease transmission losses and enhance energy access in geographically remote areas. The empirical evidence presented throughout this study shows that decentralised renewable energy systems can have a significant impact on rural electrification outcomes, especially in areas where

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grid extension is difficult due to geography or cost.The empirical evidence shown in this study confirms the positive impact decentralised renewable energy has on rural electrification, particularly in areas where grid extension proves difficult based on geography or cost. In Nigeria's coastal economy, these systems may also help diversify livelihoods in the fisheries and maritime trade through the use of these systems.

5.4 Reducing Dependence on Fossil Fuels

Electricity generation mix is still highly fossil fuel dominated with natural gas and diesel generators. This dependency has profound effects on environmental sustainability, financial stability and energy reliability. The use of tidal energy helps to transition towards a less fossil fuel dependent structure through the reduction of thermal generation in coastal demand centres. The substitution effect becomes more pronounced over time and helps to lower carbon intensity in the national electricity mix, as well as to increase the country's consistency with global decarbonisation pathways. Marine renewables are increasingly recognized in the broader energy transition discourse as a key pathway to decarbonize coastal energy systems, where there are resource complementarities with other renewables (Rusvan et al., 2024). Fostering the realization of the Climate Change Mitigation Goal at the National Level

5.5 National Action for Climate Change Mitigation

Tidal energy systems can be operated with very low greenhouse gas emissions, providing a better environmental performance than fossil-fuel based generation technologies. They also have relatively low lifecycle emissions, especially if embedded in well designed renewable energy systems. The deployment of tidal energy will also help Nigeria meet its commitments under the Paris Agreement by reducing carbon intensity, and total emissions from the power sector. Moreover, tidal energy can play a complementary role in hybrid power generation systems which can increase the overall mitigation effects. Samsó et al. (2023) stress that technologies for the exploitation of ocean energy offer significant lifecyle emission reduction, especially when implemented at a large scale in integrated renewable systems. This puts tidal energy in a favourable place to contribute to the goals of climate policy in coastal economies.

5.5 Contribution to Climate Change Mitigation

Tidal energy systems generate electricity with minimal operational greenhouse gas emissions, making them environmentally superior to fossil-based generation technologies. Their lifecycle emissions are also comparatively low, particularly when integrated into well-planned renewable energy infrastructures. For Nigeria, the deployment of tidal energy supports national climate commitments under the Paris Agreement by contributing to reductions in carbon intensity and overall emissions from the power sector. Furthermore, tidal energy can complement other renewables in hybrid systems, thereby amplifying overall mitigation outcomes. Samsó et al. (2023) emphasise that ocean energy technologies provide substantial lifecycle emission reductions, particularly when deployed at scale within integrated renewable systems. This positions tidal energy as a viable instrument for advancing climate policy objectives in coastal economies.

5.6 Supporting Sustainable Development Goals (SDGs)

Tidal energy can play a significant role in meeting a number of Sustainable Development Goals, both directly and indirectly. It is most notably for contributing to SDG 7 (Affordable and Clean Energy) by providing access to sustainable and clean electricity and promoting the diversification of energy sources. It also helps achieve SDG 13 (Climate Action) by reducing emissions and enhancing climate resilience. Moreover, tidal energy contributes to SDG 9 (Industry, Innovation and Infrastructure) through technological innovation and the development of infrastructure and new industrial capacities in marine energy. Aside from these general objectives, there are opportunities for employment in engineering, environmental management and development of coastal infrastructure. The authors of Rodríguez-Pérez et al. (2023) emphasize that marine renewable energy systems are increasingly becoming catalysts to inclusive economic development in coastal communities, especially when implemented in the context of wider blue economy policies.

VI. CHALLENGES TO TIDAL ENERGY DEVELOPMENT IN NIGERIA

Although tidal energy has a great potential in Nigeria, there are several challenges that are interlinked and can be tackled from financial, technical, institutional and infrastructural perspectives. All these constraints together are restrictive in terms of investment attractiveness and practical deployment feasibility.

6.1 High Initial Capital Costs, Technology Deployment Costs, and Levelized Cost of Energy (LCOE)

The major obstacle for the development of tidal energy is the capital-intensive nature of the infrastructure needed to deploy the technology. This encompasses the installation of subsea cables, grid interconnection systems, underwater turbines and offshore platforms. Installing and maintaining in the marine environment adds to the complexity. Furthermore, the cost of tidal energy is relatively high, at around \$0.15/MWh, when compared to other more developed renewable energy technologies such as solar PV and onshore wind. This pricing difference is especially large in less favourable financing regions, such as developing economies. The authors of Akinshilo et al. (2026) observed that capital intensity continues to be a central barrier to diversifying to renewable energy in developing coastal countries. But as technology advances, economies of scale and innovation in turbine design may slowly bring costs down over time, which can make this viable option over the long term. 6.2 Technological Limitations Tidal energy technologies are not as commercially mature as other renewable energy systems. Efficiency limitations are still a problem, especially in low velocity tidal zones or sites with unpredictable hydrodynamics. Beyond this, there are several other technical challenges such as corrosion of materials in salty marine conditions, biofouling of equipment, and stress from continuous water flow on structure. These factors add to the demands of maintenance and shorten the life of the system if not effectively managed. Victor et al. (2025) emphasize the importance of designing turbines to fit local marine conditions, to increase their efficiency and stability of functioning. The fact that they have no technical skills is a serious problem. One of the major challenges to tidal energy development in Nigeria is the lack of specialized technical skills on marine energy engineering, offshore construction and system maintenance. Advanced interdisciplinary skills are needed for the design and operation of tidal infrastructure, and these skills are not widely available in the national workforce. This skills gap leads to the necessity for foreign expertise, increasing costs of projects and decreasing capacity building of locals. Owebor et al. (2021) place special emphasis on human capital development as a key factor in the adoption of renewable energy in emerging economies, especially those of a technologically complex nature. 6.4 Weak Policy and Regulatory Framework A big institutional problem is the lack of dedicated policy and regulatory framework for tidal and marine energy development. Overall, little attention is being given to ocean energy systems, and the existing energy policies in Nigeria are focused mainly on solar, wind and hydropower. This policy gap makes investors unsure, and restricts private sector participation. In addition, the absence of licensing, environmental and investment guidelines create barriers to attractiveness of tidal energy projects. Oyedokun et al. (2022) report that one of the critical challenges in investing in renewable energy in developing countries is the lack of policy consistency and policy fragmentation.

6.2 Limited Research and Development In Nigeria, research and development activities in tidal energy are still in its infancy. Very little empirical information exists on the distribution of tidal resources, the variability in these resources by season, and on site-specific feasibility studies. Furthermore, there are very few environmental impact studies and local appropriate technological studies. This is a lack of evidence-based knowledge, limiting strategic planning and stalling innovation. Adebayo et al. (2024) state that inadequate infrastructure investment is a key constraint in the use of new renewable technologies in Sub-Saharan Africa.

6.3 Grid Integration Challenges

Technical challenges to integration of tidal power in Nigeria's current electricity grid. These include: coastal generation patterns variation, lack of transmission lines in coastal areas, and weak grid stability. It is difficult to efficiently evacuate power from many potential tidal energy sites where transmission networks are not well developed. Additionally, the unpredictability of tides means advanced grid management systems and storage integration are needed. Samsó et al (2023) note that grid integration is one of the longest standing challenges for ocean energy systems, especially in areas with poor or less developed electric grid infrastructure.

VII. FUTURE PROSPECTS OF TIDAL ENERGY IN NIGERIA AND STRATEGIC ROADMAP.

Advances in marine renewable technologies and the development of the national power infrastructure will play a key role in the future prospects of tidal energy in Nigeria, as will the nation's overall shift to a low carbon energy system. The first key aspect of this perspective is emerging tidal energy technologies. The industry is also moving away from experimental deployments, with greater focus now being placed on more effective, commercially viable systems, especially tidal stream turbines, floating generators, and modular underwater power generation units which are better suited for lower maintenance and higher energy capture in variable tidal conditions. For Nigeria, which has different hydrodynamics in the Niger Delta, Lagos Lagoon and Calabar estuary, such innovations could greatly mitigate the past technical challenges associated with deployment in sediment-laden and corrosive waters. As materials become more durable, turbine blade design is evolving with new, more efficient blades, and artificial intelligence developments in predictive maintenance further increase the potential of long-term operation in Nigerian marine environments. The issue of smart grid integration is tightly coupled with this one. Tidal energy is intermittent, but it is also very predictable, making it an ideal partner for contemporary grid systems, especially with the help of digital monitoring and automation technologies. However, Nigeria's current grid system needs significant upgrades to handle decentralized and variable renewable energy resources. Smart grid systems will play a crucial role in enabling the transmission of tidal energy from generation sites at the coast to demand centers in the inland regions, with real-time load balancing, advanced metering infrastructure and energy storage coordination being key components of the smart grid. The same integration also helps grid stability, minimizes transmission losses and strengthens the national electricity grid, especially in areas at risk of load shedding or grid collapse.

The other critical pathway for the future is hybrid renewable energy systems. Tidal energy cannot be a short to medium-term solution for Nigeria. Instead, it is more realistically placed within hybrid schemes with a mixture of solar PV technology, wind energy and possibly a small-scale hydro-power scheme. Coastal areas have significant complementarities between solar and tidal resources, with the solar resource producing its highest output during the day and the tidal resource following predictable patterns driven by the moon. Such hybridization enhances energy reliability, reduces storage requirements, and improves overall system efficiency. It also provides a more stable supply for off-grid and mini-grid applications in coastal and riverine communities, where national grid access remains limited or unreliable.

The growth of tidal energy also aligns well with the new blue economy agenda. The coastal and marine areas are already utilized for fisheries, shipping, oil and gas infrastructure, and tourism in Nigeria. The deployment of tidal energy infrastructure will add another productive dimension to this marine economic system, which could generate jobs in marine engineering, environmental monitoring, offshore construction and maintenance services. In addition to generating electricity, if managed correctly, tidal installations can have additional benefits such as coastal protection functions, including erosion control and shoreline stabilization. But a careful spatial planning must be carried out to prevent conflicts with the existing maritime activities and to guarantee the ecological sustainability in sensitive delta ecosystems. Energy security-wise, the tidal energy offers long term strategic opportunity for diversification of Nigeria's electricity mix. Its reliance on fossils and hydropower is subjecting it to price volatility, climatic variation and infrastructural constraints. Tidal energy, on the other hand, is a very predictable, locally available energy resource base, which can enhance energy autonomy. Its incorporation in national energy mix would take the strain from overused hydraulic plants and the risk from disruptions in fuel supply for thermal plants. This diversification over time can help to create more grid reliability and a more balanced regional distribution of generation capacity. Lastly, the long-term decarbonization potential of tidal energy makes it a key resource for Nigeria's climate commitments and energy transition plan. While it presently plays a relatively small role in global energy production, the lifecycle emissions profile of tidal generation is relatively stable, and the emissions from operation are relatively low. The implementation of this, thus, would help Nigeria's NDCs under international climate commitments, and enhance its footing in global sustainability frameworks. With other renewable energy technologies, tidal power can play an important role in a highly decarbonized power sector in the mid-term timeframe (by 2050), provided it receives stable policy guidance, investment support and innovation.

VIII. CONCLUSION & RECOMMENDATION

As countries shift towards eco-friendly and safe energy, they must look into alternative renewable energy sources other than solar, wind and hydropower for their growing demand for electricity, especially in countries with recurring electricity shortages. The study underscores the potential of tidal energy as a significant underutilized marine resource that could play a crucial role in Nigeria's long-term energy security and decarbonization efforts. Global developments show that there is evidence that tidal systems provide predictable generation, high energy density and strong alignment with net zero targets. However, in the Nigerian context, it is found that despite the theoretical resource potential and the capacity to deploy it, there are institutional, financial, technological and regulatory constraints that have left a significant gap. The study therefore establishes that tidal energy should be treated not as an alternative curiosity but as a strategic element within Nigeria's broader renewable energy transition framework.

- The government should develop a clear national policy on marine renewable energy. Tidal energy should be included in Nigeria's long-term energy planning. Strong regulations, targets, and incentives should be introduced to guide development.
- A dedicated body or strengthened agency should be responsible for marine and tidal energy development. Responsibilities among existing energy institutions should be clearly defined to avoid overlap and delay in decision-making.
- Nigeria should invest in research, testing, and local adaptation of tidal energy technologies. Pilot projects should be established in suitable coastal areas to test performance before large-scale deployment. Partnerships with countries already using tidal energy should be encouraged.
- Funding mechanisms should be created to support tidal energy projects. This may include public-private partnerships, green bonds, and support from international climate funds. Investors should be given tax incentives to reduce financial risk.
- Universities and research institutes should be supported to conduct studies on tidal energy potential, environmental impacts, and system design. Data collection on Nigeria's coastal energy resources should be improved and made accessible.
- Coastal communities, private investors, government agencies, and environmental groups should be involved in planning and implementation. Public awareness programmes should be introduced to improve acceptance and reduce resistance to projects.

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