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Assessing the Potential of Tidal Power Plants in Sub-Saharan Africa

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Abstract: This study assesses the potential of tidal power plants in Sub-Saharan Africa (SSA), an area with considerable yet untapped renewable energy resources. Leveraging previous research and technological advancements, this study focuses on tidal range and tidal stream power plants, exploring their feasibility in the unique coastal geography of SSA. The paper highlights the significant tidal currents along the Atlantic coast, particularly in regions such as Equatorial Guinea, which present promising opportunities for tidal energy generation. By analyzing the environmental, economic, and technical challenges and the potential benefits of deploying tidal power plants, this research aims to provide a comprehensive framework for developing sustainable and reliable renewable energy sources in SSA. This study emphasizes the need for detailed resource assessments, innovative engineering solutions, and supportive policies to realize the full potential of tidal energy in the region.

Keywords: Tidal, Environmental, Renewable, Sub-Saharan, Power

Introduction

General trends suggest that renewable energy power generation across Sub-Saharan Africa (SSA) will increase in the foreseeable future; however, the actual power resource potential is, as yet, untapped (Osiolo, 2021). The renewable potential available to Sub-Saharan Africa is still largely untapped but potentially enormous; estimates of 10,000 TWh/y are available using prioritized technologies (Aboagye *et al*., 2021). Previous studies, primarily involving European countries, have attempted to define wind, current, and tide power resource potentials for their coastal regions (Ayamolowo and Kusakana, 2024). Generally speaking, African nations possess a more favorable location relative to the strong tidal currents of the high energy density equatorial wedges than Europe, which is predominantly located in high latitude waters with significantly weaker current speeds. The higher energy density currents of the equatorial wedge offer the prospect of delivering tidal turbines that are competitive with land-based wind power as well as the merits of a combination of impact, risk, and diversity concerning more mature renewable sources more widely reported in Africa, such as solar and wind (Zegait *et al*., 2022).

Global electricity generation is challenged by the twin forces of ensuring reliably available power while conversely transitioning to clean, low-carbon resources (Osiolo, 2021). The availability of clean, efficient power is critical for economic and human development but is all too often accompanied by a growing share of carbon and pollution-emitting resources (Aboagye *et al*., 2021). This conundrum is particularly acute for Sub-Saharan Africa (SSA), where energy demand is projected to increase rapidly. Its improving economic condition helps lift hundreds of millions of people out of energy poverty. Power demands in SSA are expected to triple between 2015 and 2040, with much of the growth provided by coal-fired power plants (Ayamolowo and Kusakana, 2024). The provision of such a large quantity of new power generation capacity from coal, or indeed any fossil fuel resource, presents substantial risks and challenges to maintaining the goal of sustainable development, energy security, and environmental equitability (Zegait *et al*., 2022).

Background and Rationale

The threat design and costs for tidal stream energy plans span from regions on the brink of deployment to those in shallow water (Chowdhury *et al*., 2021). As the tidal stream-era industry plans continue to carry out feasibility and demonstration plans, it is necessary to recognize that there are no regressions to complete knowledge on property management of regions vulnerable to the effects of climate change, such as large-scale facilities, whether or not these technologies are available for metal extraction and power administration (Rahman *et al*., 2022). This study aims to estimate the potential of production by a tidal plant in SSA by considering the need to understand its development and the expectations of the climate sector in the area. The GLOMOPHD is a 1 h resolution that provides public data employed to sketch the potential of the machines for the first time. Innovation-driven urbanization, mainly driven by electricity production, promotes countries' development worldwide (Mackie *et al*., 2020). Even though Sub-Saharan Africa (SSA) emphasizes hydropower (also known as water energy) as a critical aspect of its plans to increase energy access, climate change is predicted to result in complex challenges, further improving SSA hydrological susceptibility (Angeloudis *et al*., 2020). The construction of dams and tidal power plants remains the best means of harnessing water sources that are equipped with the possibility for additional power requirements satisfaction. The construction of extensive damming facilities in SSA, in a changing climate world, with a focus primarily on the growth of water demands, has raised fears and excitement due to the destruction of salinity and nutrient stability and amphibian biodiversity and the trapping and accumulation of greenhouse gases. The annual electricity generated through tidal power plants is around 40% of global energy production.

Research Objectives

The first research objective is to develop and implement a model to assess the tidal energy potential of any given location using available Digital Elevation Maps (DEM). As a result, the model will be applied to the case of the Saloum River estuary and its outputs compared to those from field measurements taken during a week in September 2013.

The section objective is to develop an electricity generation model of a tidal power plant using a conventional propeller or a horizontal or vertical tidal current turbine to simulate as many realistic outputs as possible. These models will calculate the total amount of electricity produced annually and look more specifically at the variations in energy generation levels (diurnal and Interannual). The third and final objective is to assess the net effect of a tidal power plant on the local environment and communities. This study investigates the potential of tidal power plants for electricity production in sub-Saharan Africa. In particular, Senegal is assessed as a possible case, as this country is known for its strong tidal currents in Casamance's water.

Tidal Energy Technology

At the end of the 20th century and the beginning of the 21st century, a significant interest emerged in implementing tidal energy extraction technology due to concerns about peak oil and carbon emissions, spurring new renewable energy developments (Rahman *et al*., 2022). Most commercial-scale tidal power plants in use and under development are of the power plant type, using an artificial basin to store tidal power. Tidal power alone has the potential to supply over 20% of the estimated total electricity requirements in places where tidal ranges exceed 5 m (Neto *et al*., 2020). Since 1966, 13 experimental tidal power plants have been in operation worldwide at various stages of economic viability, with installed capacities ranging from 240 kW to 240 MW. The estimated tidal stream energy potential is around 120 GW (Jahangir *et al*., 2020). Tidal power, also known as tidal energy, is a form of hydropower that converts the energy obtained from tides into proper forms of power, mainly electricity. Tidal power is unique in that it derives directly from the relative motions of the Earth-Moon system and, to a lesser extent, the Earth-Sun system. Tides are more predictable than wind, which can intermittently reduce the output of renewable sources when it does not blow. Furthermore, tidal patterns can be predicted years in advance, unlike solar energy intermittently obscured by clouds. These factors are critical in identifying potential sites for tidal power plants. Figure (1) presents various tidal energy devices, showcasing technologies and companies involved in tidal power generation. Each device represents a unique approach to harnessing tidal energy, highlighting the diversity and innovation in marine renewable energy. These devices are designed to capture the kinetic energy of tidal currents and convert it into electricity, contributing to the global effort to produce clean, renewable energy.

Here is a brief description of each device illustrated:

1. P12
    - Company: Open hydro
    - Device: Open-centre single-rotor turbine on a tripod base
    - Power: 1 MW
    - Deployment: Summer 2015
2. SEAGEN I
    - Company: Marine current turbines
    - Device: Vertical axis tidal turbine with two rotors
    - Power: 1.2 MW
    - Deployment: 2016 or later
3. TRITON
    - Company: Black Rock Tidal Power
    - Device: Semi-submerged floating turbine array
    - Power: 2.5 MW
    - Deployment: Fall 2016
4. AR1500
    - Company: Atlantis leobhead
    - Device: Single-bladed rotor turbine with tripod support structure
    - Power: 1.5 MW
    - Deployment: 2017

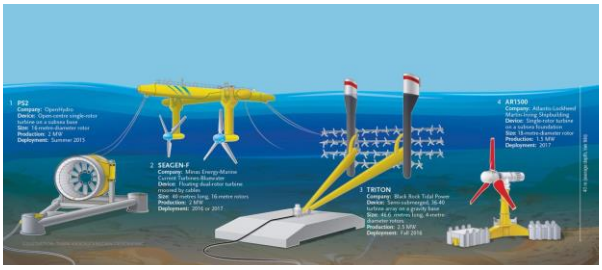

Fig. 1: Tidal energy devices

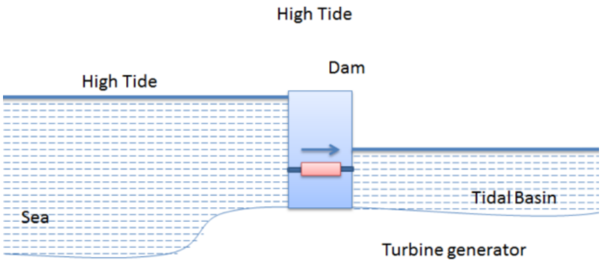

Fig. 2: Working of tidal power generation

Overview of Tidal Power Generation

The potential for macro-tidal-range (6-8 m) for both gravitational range and meso-tidal currents between Point Love and the mouth of the Congo River, spanning over 1,300 km, was explored for over 21 tidal power plants (Ideki and Ajoku, 2024). The study evaluated a 100 MW peak installed capacity over 3,500 km, selecting the Loya River Narrow with a gravitational tidal range of 18 m in the Very High Tidal Range (VHTR) and the Dawa River with a tidal range of 5.3 m in the High Tidal Range (HTR). Fourteen stations along the Eastern Coastal belt were selected, including the Loya and Dawa River mouths. The southern part of the coast can be classified as meso-tidal, while the Gulf of Guinea has a micro-tidal range (Idowu and Lasisi, 2020). Most tidal power developments today are in regions with micro-tides, such as the Russian Federation, South Korea, the UK, and Canada (Ballesteros and Esteves, 2021). Sub-Saharan Africa has a coastline of 25,000 km, making it the third largest coastline after Canada and the USA. A study of high tidal range (20-70 m) with a total power installation ranging between 50 and 150 GW (96-288 kWh/m^2/day) was performed in a pilot project near the Thwel River estuary (Jalloh *et al*., n.d). Tidal power plants utilize offshore man-made hydraulic structures (barrages, lagoons, or tidal turbines) to harness energy from tidal flows or currents. Figure (2) depicts ocean tides rising and falling, where water is stored during the rise and discharged during the fall using a dam separating the tidal basin.

Tidal ranges are classified as high, medium, or low. A tidal range is defined as micro-tidal if it is less than 2 m, meso (2-4 m), macro (4-6 m), and mega-tidal if it is more than 6 m (Rahman *et al*., 2022). Tidal power plants can contribute to renewable energy by harnessing ocean tides for electricity. With technological advancements and increasing demand for sustainable energy, tidal power exploration has gained global attention. The area between Point Love and the Congo River mouth offers a unique opportunity for tidal power generation with its macro-tidal range of 6-8 m (Neto *et al*., 2020). Strategically placing tidal power plants along this coastline can efficiently harness in-passage and out-passage currents for electricity generation. Due to their gravitational tidal ranges, the Loya River Narrow and Dawa River have been identified as ideal sites for tidal power installations. Fourteen stations along the Eastern Coastal belt have been selected for potential tidal power development, including the Loya and Dawa River mouths. These stations present favourable conditions for harnessing tidal energy. The southern part of the coast can be classified as meso-tidal, while the Gulf of Guinea experiences micro-tidal conditions. High tidal ranges (20-70 m) have been studied near the Thwel River estuary, with total power installations ranging between 50 and 150 GW (Jahangir *et al*., 2020). Such projects demonstrate tidal power's potential as a significant contributor to the global energy landscape.

Tidal power plants, designed with offshore hydraulic structures, capitalise on energy from tidal flows or currents (Chowdhury *et al*., 2021). These plants offer environmental benefits, economic advantages, and job opportunities. The predictable nature of tidal cycles ensures a reliable electricity source. Tidal power's importance is growing as the world transitions to sustainable energy. Sub-Saharan Africa, with its extensive coastlines and vast potential for renewable energy, stands to benefit significantly from tidal power projects. The region's coastlines provide a significant opportunity for generating clean energy. Tidal power exploration holds considerable promise for meeting global energy demand. From macro-tidal ranges to micro-tidal variations, tidal areas offer unique opportunities for efficient energy generation. With technological advancements, tidal power plants can become crucial to a sustainable, clean energy future.

Types of Tidal Power Plants

Tidal range power plants: Tidal range power plants transform gravitational potential energy into kinetic energy. These plants are typically situated in inlets between the sea and ocean bays or gulfs, leveraging the natural coastline shape to amplify energy potential. Notable examples include the Severn Estuary and La Rance River facilities. By narrowing the water flow, these plants effectively use the coastal geography to increase energy extraction efficiency (Rahman *et al*., 2022; Nachtane *et al*., 2020).

Tidal stream power plants: Tidal stream power plants convert the kinetic energy of tides into electrical energy. These plants are anchored to the seabed using special devices, with turbine generators extracting the energy. Although their operation introduces some hydrodynamic loss, technological advancements have mitigated these impacts, balancing energy production with environmental preservation. These plants help reduce the speed of flood and ebb flows, preserving marine ecosystems and preventing coastal erosion (Bullich-Massagué *et al*., 2020; Zhang *et al*., 2021).

Developing and implementing tidal stream power plants have significantly produced renewable energy. These innovative plants harness the immense power of tides, converting it into clean and sustainable electricity. By anchoring themselves to the seabed, they ensure maximum efficiency in energy extraction. The turbines are meticulously designed to optimise energy conversion, enhancing overall performance.

Tidal stream and tidal range power plants represent ground-breaking advancements in renewable energy. Their ability to harness natural tidal forces holds tremendous promise for a greener, more sustainable future. These plants exemplify the fusion of science, engineering, and environmental consciousness, providing a compelling solution to meet growing energy demands while minimizing harm to the planet.

Sub-Saharan Africa's Tidal Energy Potential

Tidal power plants connected to the grid could be a suitable solution to the problem of supplying electricity to the people of sub-Saharan countries. Unlike solar or wind energy, tides can be predicted accurately for long periods, making the energy produced reasonably regular. In the case of tidal energy plants, no thermal pollution is produced and there is no greenhouse effect, among other environmental benefits (Opperman *et al*., 2022). Additionally, tidal power has some well-known disadvantages compared to other energy sources, such as hydroelectricity, wind, and solar energy. However, the turbines' inaccessibility minimizes the risk of sabotage and/or theft of parts. Moreover, underwater power plants in estuaries will have a lesser environmental impact than conventional powerhouses. The author is conducting an economic feasibility study to construct the Tiff off in tidal energy plant, the first small tidal power plant in sub-Saharan Africa, to ensure a constant electricity supply for the many families there. The sub-Saharan African coastline has a length of 30,579 km and is surrounded by the Atlantic and Indian oceans. Table (2) shows the available coastline length of some selected countries. Ghana's potential to generate 2,488 GWh/year of electricity alone demonstrates the potential of tidal energy in sub-Saharan Africa. The Gulf of Guinea shows excellent potential, especially in the small gulf. Togo, Benin (with the highest potential of all sub-Saharan coastal regions), Ghana, and the Ivory Coast are particularly well-placed to benefit from this indigenous, clean, and inexhaustible source of electricity. While potential sites exist only on the east coast of Africa, lakes and dams are not yet included and can significantly increase the potential.

Geographical Considerations

This analysis identifies coastal locations where morphology assists the formation of significant tidal plains and optimises tidal energy harvesting. While a complete analysis should include non-oceanic tidal effects, the primary focus is on the dominating long-period signals essential for economically harnessing tidal power. Coastal morphology influences tidal current location and intensity, with stream power directly affected by flow interacting with turbines. A region's coastal configuration can significantly impact tidal energy potential-uniform basins aligned with tidal wave deflection experience minimal head loss and oscillating internal circulation. Favourable coastal morphology can generate convergent and divergent circulation, creating alternating flood and ebb tides. By constraining tidal flow in specific coastal sections, incoming currents can be concentrated and harnessed for energy production, similar to tidal stream plants (Foteinis, 2022; Haigh *et al*., 2020; Coles *et al*., 2021; Nachtane *et al*., 2020).

Analysis of Coastal Morphology for Tidal Energy Harvesting in Sub-Saharan Africa

Coastal Morphology and Tidal Plains Formation

The coastal morphology in Sub-Saharan Africa varies significantly, with certain regions exhibiting features conducive to the formation of tidal plains, which are crucial for effective tidal energy harvesting. These areas typically include wide continental shelves, estuaries, and regions where the coastline amplifies tidal ranges.

Wide Continental Shelves

- Mozambique and Namibia: Regions with broad continental shelves allow for greater tidal ranges as the incoming tidal wave is compressed and its height increases. The extensive continental shelf in these regions enhances the tidal amplitude, making them suitable for tidal energy projects

Estuaries and Inlets

- Niger Delta, Nigeria: The interaction of tidal and fluvial processes in estuarine regions forms significant tidal plains. The Niger Delta, being one of the largest estuarine regions in Sub-Saharan Africa, provides vast areas where tidal energy can be harvested effectively
- Rufiji Delta, Tanzania: Similar to the Niger Delta, the Rufiji Delta benefits from the interaction of tidal and riverine processes, creating extensive tidal plains ideal for energy harvesting

Morphological Amplification

- Guinea coast and South Africa: Certain coastlines are shaped to amplify the tidal wave naturally. While not as extreme as the Bay of Fundy in Canada, the Guinea Coast and parts of South Africa exhibit similar morphological features that enhance tidal ranges and energy potential

Interaction with Dominant Components of Tidal Waves

Tidal energy harvesting is most effective in locations where the interaction with tidal components such as amplitude, frequency, and flow velocity is optimized.

Amplitude:

- Natural Amplification: High tidal ranges are essential for generating significant energy. Regions with natural amplification, such as narrow bays and funnel-shaped estuaries, are ideal. These areas benefit from the increased height of tidal waves, providing a more significant potential for energy generation

Frequency:

- Semi-diurnal tides: Regular and predictable tidal cycles provide consistent energy output. The semi-diurnal (twice daily) tides in most of Sub-Saharan Africa's coastal regions are advantageous for this purpose, ensuring a reliable and steady tidal energy source

Flow velocity:

- Constrained tidal flows: Strong tidal currents are necessary to drive turbines efficiently. Locations with constrained tidal flows, such as between islands or within narrow channels, can produce high flow velocities. These areas are particularly suitable for installing tidal turbines to harness kinetic energy

Potential locations for tidal energy harvesting the Mozambique Channel:

- Location description: The Mozambique Channel, situated between Mozambique and Madagascar, features significant tidal ranges and flow velocities, making it a prime candidate for tidal energy projects
- Advantages: The channel's wide continental shelf and tidal solid currents provide an optimal environment for large-scale tidal energy harvesting

Guinea coast:

- Location description: This region includes several estuaries and inlets with favorable tidal characteristics, such as the coastlines of Ghana and Guinea-Bissau
- Advantages: The morphological amplification in this region enhances tidal ranges and the estuarine environments provide extensive tidal plains for energy development

South Africa’s west coast:

- Location description: Areas around Cape Town experience substantial tidal ranges and have the necessary infrastructure to support tidal energy projects
- Advantages: This region's combination of high tidal ranges and existing infrastructure makes it well-suited for implementing tidal energy systems

Tanzania’s Rufiji delta:

- Location description: The Rufiji Delta, with its extensive tidal plains and strong tidal currents, presents an excellent opportunity for tidal energy development
- Advantages: The delta's significant tidal plains and robust tidal flows make it an ideal location for tidal energy projects, offering environmental and economic benefits

Sub-Saharan Africa's coastal morphology offers several promising locations for developing tidal energy projects. Sub-Saharan Africa can effectively harness tidal energy by leveraging natural tidal amplification in regions like the Mozambique Channel, Guinea coast, and Rufiji Delta and capitalizing on the regular and tidal solid cycles. This provides a renewable energy source and contributes to reducing carbon emissions and achieving economic profitability through sustainable energy practices.

Figure 3 includes a map of Africa and a diagram showing coastal morphology and the formation of tidal plains in Sub-Saharan Africa.

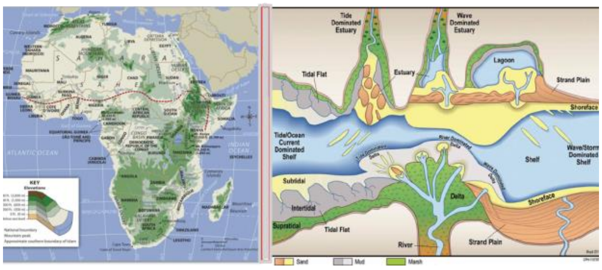

Fig. 3: Coastal morphology in Sub-Saharan Africa supports tidal energy harvesting

Map of Africa

- Topographical features: Illustrates elevations such as mountains, plateaus, and coastal plains, influencing coastal morphology and tidal dynamics
- Coastal regions: Highlights key areas like Namibia, Mozambique, and the Niger Delta, showing broad continental shelves and estuarine environments favorable for tidal energy harvesting

Coastal Morphology Diagram

- Tidal-dominated estuary: Areas like the Niger Delta form extensive tidal flats
- Wave-dominated estuary: Regions influenced by wave action
- Tidal flats: These are found in intertidal and supratidal zones and are crucial for tidal energy
- River influence: Rivers like in Tanzania’s Rufiji Delta create deltas and estuaries
- Zones: Subtidal and intertidal zones are vital for understanding tidal dynamics

Resource Assessment

The data collection method is typically deployed for resource assessments and the requirements of the models used at a later stage are different. This must be well documented to define the necessary processes and establish the data requirements. Because tidal-current models tend to be derived from barotropic models, students who study the more bottomless ocean typically receive little training in the modeling principles and constraints in shallower regions, leading to a paucity of resource models (Filimão Sitoe *et al*., 2023; Belletti and McBride, 2021; Gilau and Failler, 2020; Gebreslassie and Khellaf, 2021). Suggestions are made to address some of these needs concerning available resource models in the context of the potential future deployment of tidal-current farms in Sub-Saharan Africa. Exploiting tidal currents as a renewable energy source requires a thorough resource assessment. Data is required on the statistical distribution of the current speed and its diurnal variability at each location. Furthermore, a resource description using only average current speeds is inadequate, as locations that demonstrate a high variance around a slightly lower average current speed can be more attractive than one with a slightly larger current speed and less variability. Financial decision-making must be based on reliable output estimates and altering decisions at a later stage is costly.

Challenges and Opportunities

This is the first paper that assesses the potential of tidal power in Sub-Saharan Africa. The research builds on previous experiences from the European Seagull project in the English Channel and potential sites for grid-connected tidal applications found in Bubiyan and Darwin. The ambition is to qualify and operationalize an objective methodology that allows for a rigorous selection of the most suitable locations, considering that the electricity refinancing cost is competitive and infrastructure planning is simplified (Belletti and McBride, 2021; Baye *et al*., 2021; Mensah *et al*., 2021; Daggash and Mac Dowell, 2021). Our methodology considers a combination of tidal stream and site characteristics and grid and country specifics. While it is possible to suggest some potential sites, the results should still be seen as experimental. Ongoing advancements in the sector, such as cost reductions, new sensor types, sea-bed mapping, and co-location with floating solar PV, will also influence the final choice. However, this progress demands a more theoretical discussion of the existing site potential with its inherent technological, structural, and organizational implications. Our discussion aims to avoid over-reliance on large-scale global comparative studies and sea-bed topographic analyses. Recognizing that the tide also brings social, environmental, and technical challenges is essential. A grid-connected tidal power plant is a new technology for countries in Sub-Saharan Africa with coastal locations. Issues relate to the local ecological impact and how the energy capacity factor of the plant is affected by the neap-spring variation. Additionally, challenges exist in enhancing a tidal power plant's electrical and economic viability using battery storage. Finally, while the boundaries for site selection are derived from large-scale studies and analyses, the final decision of where and how a tidal power plant is connected to the grid involves technical challenges. These include connectivity infrastructure, voltage profiles, stability of the power system, and potential losses in the operation of a tidal site.

Technical Challenges

Hydrodynamic design and system engineering are essential to increase the drag and lift forces, protect the structure, and achieve optimal resonance excitation. The turbulence of the ambient flow, environmental loads, and reliability must also be considered. A shift in the hydrodynamic paradigm is necessary to overcome the current technical challenges, especially in high-cost environments, as conventional hydrodynamic designs remain inoperative. Increasing the output power in energy megatherium systems of approximately 100 MW will substantially reduce the sections needed to build large power generation plants (Nicholls-Lee, 2023; Hemery *et al*., 2022; Scialò *et al*., 2021). Tidal power plants can be built using existing off-the-shelf technology, making them a promising renewable energy source ripe for large-scale deployment in a short time. However, the general design of many Hydraulic Power Conversion Systems (HPCS) is suboptimal, often achieving efficiencies below 40%. These systems typically operate below optimal speed, presenting a significant challenge in tidal energy converters. According to the Betz principle, for a turbine to approach 100% efficiency, the flow speed must be reduced to zero.

Since this is not possible, the maximum efficiency of the turbine is limited to around 40%. To address these issues, innovative design approaches and technological advancements are required. Enhancing the efficiency of tidal energy converters is crucial for maximising their potential as a sustainable energy source. By improving hydrodynamic performance and optimising system engineering, significant strides can be made in the field, paving the way for more effective and economically viable tidal power plants.

Economic Viability

Sub-Saharan Africa (SSA) possesses considerable potential for tidal power. However, the potential of such niche renewable energy sources remains unexploited due to the SSA countries' low economic and political development. The main objective of this review paper is to provide an overview of the tidal energy potential of Sub-Saharan Africa by taking into account, inter alia, the regional and national settings, and the techno-economic and environmental aspects. It is shown that Sub-Saharan Africa possesses a significant tidal resource, especially off its southwestern coastline. Other countries, namely those surrounding the Gulf of Guinea, possess tidal energy potential, but the resource is currently less well known and would require lengthy marine survey campaigns. Reviewing available data from global and national databases, it has been found that the tidal energy potential of Sub-Saharan Africa is on the order of (only in Mozambique) 16.3 GW, of which 9 MW is within an economic distance of the leading national grid system. Table (1) outlines the critical factors in assessing tidal power plants' economic viability in Sub-Saharan Africa.

This table provides an overview of the factors specific to Sub-Saharan Africa that influence the economic viability of tidal power plants, helping stakeholders make informed decisions regarding investments in this renewable energy source.

Table 1: The economic viability of tidal power plants in Sub-Saharan Africa is influenced by critical factors

Factor	Description	Details/impacts specific to Sub-Saharan Africa
Initial capital costs	The upfront cost required for the construction and installation of tidal power plants	High initial costs; funding challenges due to limited financial resources
Operational and maintenance costs	Ongoing expenses for the operation and upkeep of the tidal power plant	Lower-than-fossil fuel plants; require skilled labor and regular maintenance
Energy production capacity	The amount of energy that the tidal power plant can generate	Consistent energy output; potential to meet growing energy demands
Environmental impact	The effect of tidal power plants on the surrounding ecosystem	Minimal emissions; need to manage potential impacts on marine life
Financing and incentives	Availability of funding, subsidies, and incentives from government and financial institutions'	Limited availability is critical for reducing the initial financial burden
Revenue generation	Income from selling the electricity produced by the tidal power plant	Steady revenue from reliable energy production
Payback period	The time it takes for the tidal power plant to recoup its initial investment through revenue	is Influenced by high initial costs and limited financial incentives
Levelized Cost Energy (LCOE)	Considering all costs over the plant's lifetime, average cost per unit of electricity generated	It is essential to compare cost-effectiveness with other energy sources
Economic development impact	The potential for job creation, local industry stimulation and infrastructure development	High potential for local economic growth and development
Energy security	Contribution to reducing reliance on imported fossil fuels	Enhances national energy independence and security
Policy and regulatory the framework	Supportive policies, regulations, and incentives from of the government's	Essential for project approval and long-term viability
Technological advancements	Innovations in tidal turbine technology and materials	Can reduce costs and improve efficiency; access in technology may be limited
Market conditions	Current and projected market demand for renewable energy	Growing demand for renewable energy; market conditions vary by country
Risk factors	Potential risks such as environmental challenges, technical failures and financial uncertainties	Needs to be mitigated through planning and robust project management

Case Studies

Assessment of the prospective sources of Tidal Energy: Tides, currents, and water heads close to the Atlantic coast of Equatorial Guinea:

a. Jurassic inundations in the North-western part of Ancient Africa

The Jurassic period witnessed significant geological events, including inundations that shaped the northwestern part of ancient Africa. These inundations played a crucial role in forming the current coastal morphology and tidal patterns observed today. Understanding these historical events provides insights into the sedimentation patterns, coastal topography, and hydrodynamic environment essential for assessing tidal energy potential:

b. Ensemble of Equatorial African Dike Swarms and Application of the Enrichment Model to African and Other Kimberlites

The Equatorial African dike swarms are significant geological features influencing the region's geological stability and structure. The enrichment model, commonly applied to kimberlites (volcanic rock formations known for containing diamonds), can also be applied to these dike swarms to understand the seabed's mineral composition and structural integrity. This knowledge is crucial for installing tidal energy infrastructure, ensuring it can withstand environmental stresses and provide a stable foundation for tidal power plants. 5.1.3. The pulsation Model:

c. The pulsation model describes tidal waves' periodic rise and fall, a critical factor in tidal energy generation. This model helps predict tides' amplitude and frequency, which is essential for designing turbines and other components of tidal power systems. By accurately modeling tidal pulsations, engineers can optimize the placement and operation of tidal energy converters to maximize energy extraction efficiency
d. Summary of the research results conducted in Benito's main and auxiliary estuaries

Research conducted in Benito's main and auxiliary estuaries has provided valuable data on tidal patterns, water flow velocities, and sediment transport. These estuaries have shown promising potential for tidal energy due to their significant tidal ranges and steady current flows. The research highlights specific locations within these estuaries where tidal energy extraction would be most efficient, taking into account environmental impact and energy output:

e. Assessment of water heads close to the Atlantic coast in the Republic of Equatorial Guinea

The assessment of water heads along the Atlantic coast of Equatorial Guinea has revealed the potential for robust "exchange" tidal power plants capable of generating more than 200 MW of power. This potential is primarily due to the region's favorable tide ranges and water head levels. For example, tide ranges between 5.0-4.6 m, or an average water head of 4.8 m can support the generation of up to 222 MW of power (EQ).

This assessment underscores the region's unique advantages for tidal power generation, including:

- High tide ranges: The substantial difference between high and low tides provides the necessary water flow to drive turbines efficiently
- Optimal water heads: The elevation difference between water levels during different tidal phases enhances the potential energy available for conversion into electricity
- Geological stability: The stable geological formations along the coast ensure that the infrastructure required for tidal power plants can be securely anchored

By leveraging these natural advantages, Equatorial Guinea can develop tidal power plants that meet local energy demands and contribute to the region's broader goal of increasing renewable energy capacity. Integrating advanced modeling techniques and thorough geological assessments ensures these developments are efficient and sustainable, minimizing environmental impacts while maximizing energy output.

Existing Tidal Power Plants in Africa

While in Europe and most developed countries, this kind of plant has ceased to be an option for new installations due to the need for a long and shallow coastline, generally extra calcareous, the appearance of this kind of hydro plant in sub-Saharan Africa is less limited by the first of these constraints because of their large number of coastal areas with favorable characteristics (Filimão Sitoe *et al*., 2023). Even in the case that appropriate locations are later defined and not polluted by contaminants, the real reason for the low implementation costs of this kind of power plant consists of the lack of a competitive capability within more traditional backup electrical sources such as large hydro plants, thermal plants, or combined cycle natural gas-fueled power plants (Belletti and McBride, 2021). A minimal number of tidal current power plants have already been built worldwide. The French La Rance Plant, with a capacity of 240 MW, and the Korean Shihwa Lake Plant, 254 MW, are two hydro plants using this clean energy source. The first has contributed to France with 0.01% of their electrical production for 40 years.

Table 2: Projected Tidal Power Plants in Africa

Project name	Country	Status	Capacity (MW)	Description
West African tidal	West Africa	Proposed	TBD	The conceptual stage aims to explore tidal energy potential along the West African coast
Inhambane Bay Project	Mozambique	Feasibility study	TBD	Proposed project to harness tidal energy in Inhambane bay
Kenyan coastal study	Kenya	Research phase	TBD	Study to assess the potential for tidal energy along the Kenyan coast
Bizerte Lagoon	Tunisia	Conceptual stage	TBD	Exploring tidal and wave energy potential in Bizerte lagoon
False Bay Tidal	South Africa	Feasibility study	TBD	Investigating tidal energy potential in False Bay near Cape Town

South Korea, unlike France, uses this installation, which has a plant life of over 20 years, to reduce the cost of thermal and nuclear-supplied electrical power (Mensah *et al*., 2021). As of the current state of knowledge, there are no fully operational tidal power plants in Africa. However, some projects are in various stages of development and planning. Table (2) summarises these projects.

Note

TBD: To be determined. The exact capacities of these projects are yet to be specified as they are in various preliminary stages of research, feasibility, and planning.

Description: Details about each project's specific stages and aims, highlighting tidal energy projects' exploratory and developmental nature in Africa.

Capacity (MW) represents megawatts' planned or potential energy output. Since these projects are still in their initial stages, exact figures are unavailable.

This table highlights the emerging interest in tidal power in Africa, indicating potential future developments in this renewable energy sector.

Successful Implementation Strategies

Project financing is also key in bridging the gap between rapid industry growth and tidal power projects' long development lead time. It is believed that a plethora of institutional investment money seeking similar investment opportunities will be channelled into tidal projects once the sector is more mature and stakeholders willing to accept a more manageable investment risk might benefit indirectly from this money realising early and/or increased profits commensurate with their initial acceptance of more significant uncertainties. Encouraging government initiatives to support innovative public sector financing is consequently required. Finally, empirical CRM (Customer) concepts could be developed to facilitate small energy time sales as part of the overall financing of tidal power plants by better-implementing communication and customer acquisition infrastructures.

Successful governance strategies to support tidal power plants were identified in the European tidal power industry and involve a combination of public and private initiatives such as regulated tariffs, long-term power purchasing agreements, investment or production credits, subsidies, negative interest rates on loans from public banks, national investment guarantees, fiscal incentives, and public equity positions in projects. This approach could be at least partly emulated by the countries concerned. Solid and deliberate actions from governments will likely be required if tidal power plants are to become operational shortly, as it is well-recognized that it may take a long time to develop an industry as specialised as this one is. Such actions include setting renewable energy targets, ensuring the necessary legislative, regulatory, and fiscal environment, and adjusting sector-specific regulations for conventional power sources. A further measure, the organisation of (inter) national support and cooperation, should not be underestimated by African countries.

Conclusion

The study highlights the immense potential for tidal power generation in Sub-Saharan Africa, particularly along the Atlantic coast, where favourable tidal conditions exist. Both tidal range and tidal stream power plants offer significant opportunities for sustainable energy production, addressing the region's growing electricity demands while minimising environmental impact. Key findings suggest that regions like Equatorial Guinea could benefit substantially from tidal power plants, with specific sites showing promising conditions for efficient energy extraction. Despite the advantages, deploying tidal power plants in SSA faces several challenges, including high initial capital costs, technical hurdles, and the need for robust policy frameworks. However, ongoing technological advancements and strategic planning can mitigate these challenges, paving the way for successful implementation. The study underscores the importance of comprehensive resource assessments, innovative design approaches, and supportive government policies to harness tidal energy potential effectively. In conclusion, tidal power plants represent a viable and promising solution for renewable energy generation in SSA. By capitalizing on the region's natural tidal resources, these plants can contribute significantly to meeting the increasing energy demands sustainably and reliably, fostering economic growth and environmental conservation. This research provides a foundation for future studies and projects to develop tidal energy infrastructure in Sub-Saharan Africa.

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Author’s Contributions

Adeyinka Victor Adebayo: Conceptualized the research idea, designed the study framework, and contributed significantly to writing and revising the manuscript.

Samuel Oladeji: Provided technical expertise in developing the manuscript and contributed to writing discussion sections.

Hussein Kehinde Adebayo: Participated in the literature review and assisted in the methodology development.

Ismaheel Oyeyemi Oladejo: Reviewed and provided critical feedback on the manuscript.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

References

Aboagye, B., Gyamfi, S., Ofosu, E. A., & Djordjevic, S. (2021). Status of renewable energy resources for electricity supply in Ghana. *Scientific African*, *11*, e00660. https://doi.org/10.1016/j.sciaf.2020.e00660

Angeloudis, A., Kramer, S. C., Hawkins, N., & Piggott, M. D. (2020). On the potential of linked-basin tidal power plants: An operational and coastal modelling assessment. *Renewable Energy*, *155*, 876–888. https://doi.org/10.1016/j.renene.2020.03.167

Ayamolowo, O. J., & Kusakana, K. (2024). Assessment of Renewable Energy Development in Africa Using the Swot Analysis Model: The Cases of South Africa, Nigeria, Egypt, and Kenya. *SSRN*. https://doi.org/10.2139/ssrn.4788346

Ballesteros, C., & Esteves, L. S. (2021). Integrated Assessment of Coastal Exposure and Social Vulnerability to Coastal Hazards in East Africa. *Estuaries and Coasts*, *44*(8), 2056–2072. https://doi.org/10.1007/s12237-021-00930-5

Baye, R. S., Ahenkan, A., & Darkwah, S. (2021). Renewable energy output in sub Saharan Africa. *Renewable Energy*, *174*, 705–714. https://doi.org/10.1016/j.renene.2021.01.144

Belletti, E., & McBride, M. (2021). Against the Tide: Potential for Marine Renewable Energy in Eastern and Southern Africa. *Consilience*, *23*, 1–14. https://doi.org/10.7916/consilience.vi23.7198

Bullich-Massagué, E., Cifuentes-García, F.-J., Glenny-Crende, I., Cheah-Mañé, M., Aragüés-Peñalba, M., Díaz-González, F., & Gomis-Bellmunt, O. (2020). A review of energy storage technologies for large scale photovoltaic power plants. *Applied Energy*, *274*, 115213. https://doi.org/10.1016/j.apenergy.2020.115213

Chowdhury, M. S., Rahman, K. S., Selvanathan, V., Nuthammachot, N., Suklueng, M., Mostafaeipour, A., Habib, A., Akhtaruzzaman, Md., Amin, N., & Techato, K. (2021). Current trends and prospects of tidal energy technology. *Environment, Development and Sustainability*, *23*(6), 8179–8194. https://doi.org/10.1007/s10668-020-01013-4

Coles, D., Angeloudis, A., Greaves, D., Hastie, G., Lewis, M., Mackie, L., McNaughton, J., Miles, J., Neill, S., Piggott, M., Risch, D., Scott, B., Sparling, C., Stallard, T., Thies, P., Walker, S., White, D., Willden, R., & Williamson, B. (2021). A review of the UK and British Channel Islands practical tidal stream energy resource. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *477*(2255), 20210469. https://doi.org/10.1098/rspa.2021.0469

Daggash, H. A., & Mac Dowell, N. (2021). Delivering low-carbon electricity systems in sub-Saharan Africa: insights from Nigeria. *Energy & Environmental Science*, *14*(7), 4018–4037. https://doi.org/10.1039/d1ee00746g

Filimão Sitoe, A., Hoguane, A. M., & Haddout, S. (2023). The ocean as a source of renewable energy in sub-Saharan Africa: sources, potential, sustainability and challenges. *International Journal of Sustainable Energy*, *42*(1), 436–460. https://doi.org/10.1080/14786451.2023.2204378

Foteinis, S. (2022). Wave energy converters in low energy seas: Current state and opportunities. *Renewable and Sustainable Energy Reviews*, *162*, 112448. https://doi.org/10.1016/j.rser.2022.112448

Gebreslassie, K. G., & Khellaf, A. (2021). A Review on Energy Access: A Case Study in Africa. *2021 International Conference on Electrical, Computer and Energy Technologies (ICECET)*, 1–6. https://doi.org/10.1109/icecet52533.2021.9698488

Gilau, A. M., & Failler, P. (2020). Economic assessment of sustainable blue energy and marine mining resources linked to African Large Marine Ecosystems. *Environmental Development, 36*, 100548. https://doi.org/10.1016/j.envdev.2020.100548

Haigh, I. D., Pickering, M. D., Green, J. A. M., Arbic, B. K., Arns, A., Dangendorf, S., Hill, D. F., Horsburgh, K., Howard, T., Idier, D., Jay, D. A., Jänicke, L., Lee, S. B., Müller, M., Schindelegger, M., Talke, S. A., Wilmes, S., & Woodworth, P. L. (2020). The Tides They Are A-Changin': A Comprehensive Review of Past and Future Nonastronomical Changes in Tides, Their Driving Mechanisms, and Future Implications. *Reviews of Geophysics*, *58*(1), e2018RG000636. https://doi.org/10.1029/2018rg000636

Hemery, L. G., Mackereth, K. F., & Tugade, L. G. (2022). What's in My Toolkit? A Review of Technologies for Assessing Changes in Habitats Caused by Marine Energy Development. *Journal of Marine Science and Engineering, 10*(1), 92. https://doi.org/10.3390/jmse10010092

Ideki, O., & Ajoku, O. (2024). Scenario Analysis of Shorelines, Coastal Erosion, and Land Use/Land Cover Changes and Their Implication for Climate Migration in East and West Africa. *Journal of Marine Science and Engineering, 12*(7), 1081. https://doi.org/10.3390/jmse12071081

Idowu, T. E., & Lasisi, K. H. (2020). Seawater intrusion in the coastal aquifers of East and Horn of Africa: A review from a regional perspective. *Scientific African*, *8*, e00402. https://doi.org/10.1016/j.sciaf.2020.e00402

Jahangir, M. H., Shahsavari, A., & Vaziri Rad, M. A. (2020). Feasibility study of a zero emission PV/Wind turbine/Wave energy converter hybrid system for stand-alone power supply: A case study. *Journal of Cleaner Production*, *262*, 121250. https://doi.org/10.1016/j.jclepro.2020.121250

Jalloh, A., Faye, M. D., Roy-Macauley, H., Sérémé, P., Zougmoré, R., Thomas, T. S., & Nelson, G. C. (n.d.). *The part of Africa designated as West Africa is made up of 16 countries—Benin, Burkina Faso, Cape Verde, Côte d'Ivoire*. (pp: 1-35).

Mackie, L., Coles, D., Piggott, M., & Angeloudis, A. (2020). The Potential for Tidal Range Energy Systems to Provide Continuous Power: A UK Case Study. *Journal of Marine Science and Engineering*, *8*(10), 780. https://doi.org/10.3390/jmse8100780

Mensah, T. N. O., Oyewo, A. S., & Breyer, C. (2021). The role of biomass in sub-Saharan Africa's fully renewable power sector the case of Ghana. *Renewable Energy*, *173*, 297–317. https://doi.org/10.1016/j.renene.2021.03.098

Nicholls-Lee, R. (2023). Development of a novel, robust, near-shore, wave energy converter for energy security in remote communities. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, *237*(4), 793–804. https://doi.org/10.1177/14750902231172821

Nachtane, M., Tarfaoui, M., Goda, I., & Rouway, M. (2020). A review on the technologies, design considerations and numerical models of tidal current turbines. *Renewable Energy*, *157*, 1274–1288. https://doi.org/10.1016/j.renene.2020.04.155

Neto, P. B. L., Saavedra, O. R., & Oliveira, D. Q. (2020). The effect of complementarity between solar, wind and tidal energy in isolated hybrid microgrids. *Renewable Energy, 147*, 339–355. https://doi.org/10.1016/j.renene.2019.08.134

Opperman, J. J., Camargo, R. R., Laporte-Bisquit, A., Zarfl, C., & Morgan, A. J. (2022). Using the WWF Water Risk Filter to Screen Existing and Projected Hydropower Projects for Climate and Biodiversity Risks. *Water*, *14*(5), 721. https://doi.org/10.3390/w14050721

Osiolo, H. H. (2021). Impact of cost, returns and investments: Towards renewable energy generation in Sub-Saharan Africa. *Renewable Energy*, *180*, 756–772. https://doi.org/10.1016/j.renene.2021.08.082

Rahman, A., Farrok, O., & Haque, M. M. (2022). Environmental impact of renewable energy source based electrical power plants: Solar, wind, hydroelectric, biomass, geothermal, tidal, ocean, and osmotic. *Renewable and Sustainable Energy Reviews*, *161*, 112279. https://doi.org/10.1016/j.rser.2022.112279

Scialò, A., Henriques, J. C. C., Malara, G., Falcão, A. F. O., Gato, L. M. C., & Arena, F. (2021). Power take-off selection for a fixed U-OWC wave power plant in the Mediterranean Sea: The case of Roccella Jonica. *Energy*, *215*, 119085. https://doi.org/10.1016/j.energy.2020.119085

Zegait, R., Bentraia, M. R., Bensaha, H., & Azlaoui, M. (2022). Comparative Study of a Pumping System Using Conventional and Photovoltaic Power in the Algerian Sahara (Application to Pastoral Wells). *International Journal of Engineering Research in Africa*, *60*, 63–74. https://doi.org/10.4028/p-6sxg2q

Zhang, Y., Zhao, Y., Sun, W., & Li, J. (2021). Ocean wave energy converters: Technical principle, device realization, and performance evaluation. *Renewable and Sustainable Energy Reviews*, *141*, 110764. https://doi.org/10.1016/j.rser.2021.110764