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Integrating Tidal Energy into Sub-Saharan Africa's Power Mix: A Strategic Framework for Renewable Energy Expansion

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Abstract: Sub-Saharan Africa grapples with severe energy poverty, with around 600 million people without reliable electricity. Despite the region's significant renewable energy potential, tidal energy stands out as a promising yet underutilized avenue for diversifying the energy mix and fostering sustainable development. This study explores the feasibility of incorporating tidal energy into Sub-Saharan Africa's power framework, evaluating its implementation's technical, environmental, and economic hurdles. The findings suggest that while tidal energy offers a consistent and trustworthy source of renewable electricity, its expansion is hindered by infrastructural challenges, high initial costs, and regulatory ambiguities. To support the effective integration of tidal energy, a strategic framework is suggested, concentrating on four essential elements: policy and governance, to provide stable regulatory contexts and investment incentives; infrastructure development, to improve grid connectivity and technical preparedness; research and development, to encourage innovation that boosts efficiency and lowers costs; and stakeholder engagement, to involve local communities and build public-private partnerships that improve project sustainability. The research concludes that, with the right policy frameworks, investment, and technological progress, tidal energy could play a crucial role in the region's renewable energy transformation, bolstering energy security and economic development while addressing environmental challenges. Furthermore, the study highlights the necessity of a collaborative approach among various stakeholders to tackle the obstacles faced in tidal energy deployment, underlining the need for regional and international cooperation to promote sustainable energy solutions for Sub-Saharan Africa.

I. Introduction

With its persistent energy poverty challenges, Sub-Saharan Africa needs a strategic approach to expand renewable energy development and introduce tidal energy generation efficiently. The Indian Ocean's wave and tidal energy potential offer a unique opportunity to combat energy poverty while driving economic development. Submarine energy generation from tidal resources can supplement planned terrestrial and solar projects cost-effectively. A strategic approach is necessary to expand renewable energy development and introduce tidal energy generation efficiently. Around 600 million people, or 70 million households, in Sub-Saharan Africa, lack access to a central electricity grid. Due to economic, environmental, and political constraints, existing technologies have struggled to bridge this gap. However, renewable energy remains a promising long-term solution, though significant efficiency and cost improvements are required. Offshore wave and tidal energy have garnered global interest. These energy sources originate from oceanic winds and are influenced by basin geometry and topography. Currently, tidal energy is mainly harnessed off North-Western Europe, Canada, and the Bering Strait coasts. However, friction-induced head losses from large-pressure gradient flows near continental shelves pose installation challenges. Shoreline erosion and transported sediment also threaten energy extractors by damaging their components. Though promising, tidal currents are difficult to forecast beyond several hours and require lower speeds than hydrokinetic systems.

Electricity generation in Sub-Saharan Africa is projected to more than double from 640 TWh in 2012 to 1,540 TWh by 2040 [4]. This growth is driven by population expansion, economic development, and industrialisation. The energy mix is shifting, with coal remaining dominant, increasing from 27% in 2012 to 37% in 2040 [5]. Hydropower, once the most significant contributor at 58%, is expected to decline to 30% due to climate variability [6]. Gas is projected to rise significantly from 9% to 26%, providing a flexible alternative to coal and hydro [7]. Oil's share remains at 4%, while renewables, including solar, wind, biomass, and CSP, are expected to grow to around 20% [8]. Nuclear power remains minor due to high costs and regulatory challenges [9]. These shifts highlight the need for investments in infrastructure, grid modernisation, and policy support to balance energy security and sustainability [10].

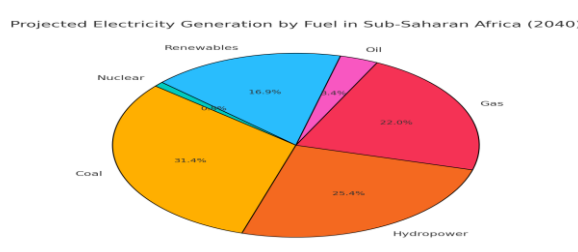

Figure 1: Projected Electricity Generation by Fuel in Sub-Saharan Africa (2040)

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II. Overview of Tidal Energy

Tidal energy is, in essence, the generation of electricity derived from the natural ebb and flow of water bodies on Earth. This continuous movement directly results from the gravitational forces exerted by the Moon and the Sun as they influence the Earth. The gravitational pull results in the oceans bulging outward while the Earth rotates, yielding kinetic energy manifested through the currents formed by this movement [4]. These tidal flows are consistent and reliable, occurring approximately twice every 24-hour cycle at each specific location, making them highly predictable [5]. This predictable nature of tidal energy provides a considerable advantage in determining when energy will be generated, allowing for a more certain energy output than the variability associated with wind and sunlight. Consequently, it facilitates a quantifiable long-term yield [6]. The technology for generating tidal energy can be classified into two primary forms: tidal stream generators and barrages. Tidal streams function similarly to underwater wind turbines, harnessing the flow of tidal currents to rotate the turbine blades, producing electricity [7].

On the other hand, tidal barrages are relatively more intricate systems. A barrage operates as a significant dam built across an estuarine river, integrating hydro turbines within its structure. As the tide rises, the potential energy of the water also increases, leading to the development of a substantial head differential. This head pressure propels water through the turbines, generating electricity [8]. Remarkably, a tidal barrage can generate power during the flood and ebb tides, collectively occurring up to four times daily. This characteristic enhances its ability to generate electricity on demand [4]. Table 1 provides a concise and structured summary of the key elements required for integrating tidal energy into Sub-Saharan Africa.

Table 1: Overview of Tidal Energy Integration in Sub-Saharan Africa

Key Aspect	Description
Potential for Tidal Energy	Sub-Saharan Africa boasts significant tidal energy potential, particularly along the West Coast, where tidal ranges and strong currents exist. This underdeveloped technology holds a promising future for the region, offering hope for a sustainable and reliable energy source.
Challenges	Technical, environmental, and economic challenges hinder the adoption of tidal energy, including a lack of infrastructure, high costs, and ecosystem impacts.
Technical and Infrastructural Barriers	Insufficient research and technological expertise, lack of grid connectivity, and minimal tidal energy infrastructure currently limit deployment.
Environmental Considerations	The potential disruptions to marine ecosystems, changes in sediment transport, and impact on fisheries necessitate thorough Environmental Impact Assessments (EIAs). This underscores the need for responsible decision-making and the importance of considering all potential impacts.
Economic Viability	High capital costs for installation and maintenance, uncertain return on investment, and lack of financial incentives pose economic barriers to tidal energy projects.
Policy and Regulatory Framework	Encouraging tidal energy investment requires stable governance, supportive policies, investment incentives, and well-defined renewable energy tariffs. Policymakers play a crucial role in creating and implementing these frameworks, underscoring the urgency and importance of their actions.
Investment and Financing	Public-private partnerships, foreign direct investment, and research grants are essential to drive tidal energy development.
Research and Development (R&D)	Continuous advancements in tidal energy technologies are needed to improve efficiency, reduce costs, and enable large-scale deployment.
Community Engagement	To ensure long-term success, local coastal communities must be involved in project planning, benefit-sharing mechanisms, and decision-making.
Strategic Framework for Implementation	1. Establish investment-friendly policies. 2. Develop grid infrastructure for tidal power. 3. Strengthen R&D in tidal energy. 4. Enhance stakeholder engagement and public awareness.
Opportunities	Tidal energy can improve energy security, support industrial growth, and contribute to sustainable development and climate change mitigation.

Numerous advantages arise from the exploitation of tidal energy. Tidal flows represent one of the most predictable and reliable renewable energy sources today. The regularity and foreseen patterns of the tides allow for accurate forecasting regarding the resource's availability and the practical estimation of the tidal energy that can be extracted [5]. Another benefit is that tidal flows are present along most coastlines, driven by universal gravitational forces. This broad potential for electricity generation is expansive and far-reaching, meaning countless individuals could benefit from the power created through tidal energy systems [6]. Furthermore, tidal energy is a denser form of energy when compared to other renewable sources. For a given flow volume, tidal currents typically produce substantially more energy than wind speeds of a similar magnitude. This leads to the conclusion that tidal stream generators can harness large electricity outputs from relatively small systems, often designed to be well-submerged beneath the water's surface [7]. Enabling energy generation through tidal systems thus presents a unique opportunity in our pursuit of sustainable

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III. Renewable Energy Landscape in Sub-Saharan Africa

Sub-Saharan Africa has significant potential for renewable energy development due to its diverse climate and geography, providing vast untapped solar, wind, hydro, tidal, and bioenergy sources. Renewables are essential for ensuring the region's long-term energy needs are met, as the population is predicted to grow by 2 billion between 2010 and 2050, combined with rapid urbanisation and industrialisation [10]. The region is also highly susceptible to the impacts of climate change. Renewable energy plays a significant role in sustainable and climate-resilient economic growth and could utilise African resources to meet energy needs while reducing carbon emissions [11]. Growing populations, changing climate patterns, and rapid urbanisation have led to regularly prolonged energy blackouts. Nearly 600 million people in the region remain unconnected to an energy grid [10]. Access to sustainable energy services is essential for social and economic progress in Africa, yet around two-thirds of Africans still rely on bioenergy for heating and cooking [11]. Sub-Saharan Africa is one of the most promising regions for renewable energy initiatives. The geographic, climate, and environmental conditions in Sub-Saharan Africa are well-suited to the development of renewable energy sources.

The Renewable Energy Policy Initiative aims to support the preparation and development of renewable projects. There remains significant underdevelopment of commercial low-carbon energy sources, indicating that vast untapped investment opportunities exist in the sector [10]. Sub-Saharan African countries often receive international support in developing renewable technologies to enhance energy security, increase energy access, and reduce greenhouse gas emissions [11]. Various policy and regulatory frameworks have been established to support the region's expansion of renewable energy technologies. Policies, strategies, financial incentives, and the removal of barriers have been implemented to stimulate the renewable energy market. However, the absence of supportive policy frameworks, economic constraints, insufficient grid infrastructure, poor management and operational capabilities, a general lack of awareness, and a low capacity to manage, develop, and operate renewable sources currently hinder their development in Sub-Saharan Africa [10]. Local communities play a crucial role in advancing the deployment of renewable energy technologies. Local ownership and stakeholder participation ensure genuine benefits to the community and maximise the cumulative socioeconomic benefits of renewable project development [11]. Nevertheless, progress towards renewable energy technologies in Sub-Saharan Africa has been limited. Political instability, inadequate regulatory frameworks, an immature private sector, and generally vague strategies have prevented the industrial implementation of renewable energy schemes in the region [10]. Strengthening the political landscape at a regional level, ensuring the implementation of agreed-upon regional initiatives, and creating the necessary pools of capital are the main prerequisites for a quicker transition to renewable technologies in Sub-Saharan Africa [11].

IV. Challenges and Opportunities for Tidal Energy Integration

Technical and Infrastructural

In the context of Sub-Saharan African countries, the potential for harnessing tidal energy generation is currently constrained, primarily limited to regions along the West Coast, where prominently noticeable tidal ranges can be found [12]. Consequently, a thorough and comprehensive review of existing developments in this sector and an analysis of the technical feasibility of tidal energy conversion along these coastlines is crucial [13].

At this juncture, significant limitations arise from insufficient dissemination of critical information and an alarming shortage of technological expertise within the tidal energy sector [14]. These prevailing factors considerably hinder the enthusiasm and interest in integrating tidal energy solutions into the broader energy mix. Therefore, it becomes increasingly evident that possessing proper and thorough knowledge is crucial to accurately appraise the viability of previously proposed projects to develop tidal energy applications [15]. This wealth of knowledge will, in turn, aid in creating a comprehensive overview of the myriad challenges posed by existing infrastructure and the significant technical limitations that must be addressed to effectively promote and advance the tidal energy sector in future endeavours [12].

Environmental

While renewable resources such as tidal energy are generally recognised and viewed favourably due to their potential for sustainability, it is imperative to acknowledge that significant concerns have been raised regarding the environmental impacts of such technologies [13]. These impacts may include disruptions to local ecosystems and alterations to local deposition and flushing rates, which could lead to unforeseen consequences [14]. Given the resources available within these local environments, an objective and judicious overview of their exploitation is necessary. This assessment must diligently balance the urgent and growing need for increased renewable energy production with the imperative of minimising any adverse impacts on local ecosystems and environments [15]. An Environmental Impact Assessment (EIA) –-based approach for evaluating the environmental repercussions of previously proposed tidal energy projects brings forth a range of socioeconomic and health concerns that must not be overlooked in the planning and execution stages [12].

Economic

Considering that installing and maintaining tidal energy devices necessitate substantial capital investment, it is essential to thoroughly assess the economic viability of extracting and harvesting local tidal resources [13]. Before such potentially low-technology readiness level (TRL) projects can be realistically considered for implementation within the energetic framework of

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these regions, the pressing question of whether the economic advantages of such installations will ultimately outweigh the associated costs must be comprehensively answered [14]. Ensuring an objective economic assessment allows all stakeholders to make informed decisions grounded in economic reality [15]. This evaluation is critical for determining whether tidal energy development in Sub-Saharan Africa is financially justifiable and can contribute meaningfully to the region's sustainable energy transition [12].

V. Key Components of a Strategic Framework

There is a rapidly growing acceptance of the need for renewable energy sources over traditional coal, oil, or gas. However, in many places, even when considered collectively, renewable energy falls short of supplying stable, continuous power on a large scale. Some regions, particularly those with widely varying coastlines and strong tidal flows, have the potential to harness tidal stream energy, a relatively immature technology that remains underutilised [16]. Sub-Saharan Africa, except South Africa, has a relatively weak traditional power generation infrastructure. In this context, tidal stream power plants could complement existing infrastructure in some locations and be a foundational energy source in others. Policy, technology, and community engagement are necessary to ensure optimal results [17]. The first component of the strategic framework for tidal energy development in Africa involves creating conditions conducive to investment. Stable and predictable governing conditions facilitate informed investment decisions. This requires support for both tidal energy specifically—through a consistent policy framework—and renewable energy more generally, including tariff incentives [16]. A favourable investment environment must offer a competitive return on investment to attract private and institutional investors.

The second component focuses on the necessary infrastructure for tidal power generation and distribution. This entails grid upgrades, some of which may also be required for the broader adoption of distributed renewable energy. The potential to attract investment in these projects is closely linked to the overall policy environment and the availability of financial incentives for renewable energy expansion [17]. The third component emphasises frontier research and development (R&D) in tidal stream energy. This is crucial, as a lack of continued technological advancements would prevent the sector from achieving commercial viability in the long term. Energy research funding is typically distributed across multiple channels, including government departments, public corporations, and research councils, highlighting the need for coordinated funding strategies [16]. The final component of the strategic framework pertains to stakeholder engagement and benefit sharing. This requires a broad approach involving multiple actors, such as government departments, the private sector, local coastal communities, and the wider South African population. Although this presents numerous challenges, it also underscores the opportunities associated with tidal energy deployment, particularly in fostering economic growth, energy security, and community-driven development initiatives [18]. Table 2 provides a structured overview of the essential components for a strategic framework to successfully integrate tidal energy into Sub-Saharan Africa.

Table 2: Key Components of a Strategic Framework for Tidal Energy

Component	**Description**
1. Policy and Governance	Establish clear, stable, and supportive regulatory frameworks to attract investment in tidal energy projects and ensure long-term policy consistency for renewable energy development.
2. Investment and Financing	Develop financial incentives, subsidies, and public-private partnerships to reduce the high capital costs associated with tidal energy deployment.
3. Infrastructure Development	Upgrade national and regional power grids to accommodate tidal energy. Develop the necessary port and maritime facilities for installation and maintenance.
4. Research and Development (R&D)	Invest in technological advancements to improve tidal energy systems' efficiency, reliability, and cost-effectiveness. Support innovation through research institutions and industry collaborations.
5. Environmental and Social Impact	Conduct thorough Environmental Impact Assessments (EIAs) to mitigate ecological disruptions, ensure local community involvement, and implement benefit-sharing mechanisms.
6. Capacity Building and Skills Development	Develop specialised training programs and knowledge transfer initiatives to enhance local expertise in tidal energy technologies and project management.
7. Stakeholder Engagement	To ensure inclusive decision-making and project sustainability, Foster collaboration between governments, private sector investors, research institutions, and coastal communities.
8. Market Development and Integration	Establish frameworks for integrating tidal energy into national energy markets. Ensure fair pricing mechanisms and competitive tariffs to encourage renewable energy adoption.
9. Risk Management	Identify and mitigate potential technical, financial, and operational risks associated with tidal energy projects. Implement insurance mechanisms and contingency planning.
10. Regional and International Collaboration	Leverage cross-border cooperation, knowledge-sharing initiatives, and partnerships with international organisations to accelerate the deployment of tidal energy solutions.

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VI. Conclusion and Recommendations

This essay emphasizes the critical need and potential for integrating tidal energy into the Sub-Saharan African energy mix during a crucial phase of renewable energy growth. It also recognizes the challenges and risks associated with achieving this ambitious objective. The essay illustrates how tidal energy projects can deliver numerous benefits to this developing continent, particularly by enhancing energy security and economic development in a region that suffers from energy poverty but possesses exceptional tidal resources. Concurrently, primary and secondary data highlight the obstacles to this initiative, stressing the urgent need for a transnational, multi-sector, and multi-level strategic framework to fully leverage the development potential for local and global sustainable prosperity. The multi-dimensional strategic framework proposed herein offers a comprehensive and innovative approach to advancing tidal energy. It aims to guide policymakers, stakeholders, and researchers in prioritizing resource allocation, maximizing synergies, and preventing conflicts as they work together to promote inclusive and sustainable Blue energies. Several practical and actionable recommendations are put forward to support this strategic framework's tangible and systematic application. Primarily, a network approach is recommended to unite various national, regional, and international platforms, coalitions, and initiatives, leveraging the global momentum to foster synergies, enable resource-sharing and exchange, and drive technological innovation while steering clear of redundancies and counterproductive competition. By unifying financial, technological, and human resources from governmental and non-governmental entities, this collaborative networking can significantly enhance the transformative potential and scale of positive outcomes, reduce harmful repercussions, and render adaptive management less contentious and more effective in blue ecosystems' complex and uncertain dynamics.

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