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TECHNICAL ISSUES IN HARNESSING BLUE ENERGY: A POWER SYSTEM PERSPECTIVE

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ABSTRACT

This paper seeks to explore the impact and technical issues in blue energy harnessing and its potential threats and benefits. Blue energy generation explores the sustainable utilization of oceanic resources to generate clean and renewable energy. This involves harnessing energy from tidal, wave, and thermal gradients, emphasizing the potential of blue energy as a reliable and eco-friendly power source. This abstract delves into technological advancements, environmental impact assessments, and the role of blue energy in addressing global energy challenges coupled with the way forward in global energy balance.

KEYWORDS; Blue energy, technical issues, harnessing, osmotic pressure, environmental impact, generation.

I. INTRODUCTION

Harnessing blue energy, also known as osmotic or salinity gradient power, involves exploiting the energy released when freshwater and saltwater mix [1]. From a power system perspective, it typically involves technologies like pressure retarded osmosis (PRO) or reverse electrodialysis (RED according to [2],[3]. These methods leverage on the osmotic pressure difference to generate electricity. Challenges include membrane efficiency, scale-up issues, and environmental impacts, making ongoing research crucial for optimizing blue energy systems [1]. Research recently developed a water-tube-based triboelectric nanogenerator that can efficiently convert various irregular and low-frequency mechanical energies, including ocean wave energy, into electricity, providing a new avenue for the development of ‘blue energy [4, p5].

II. LITERATURE REVIEW

Researchers nowadays have been exploring different approaches for harnessing ocean energy to solve world energy crisis and pollution problems caused by thermal power generation. One such method is the usage of triboelectric nanogenerator (TENG), which makes use of triboelectric effect and electrostatic induction to harvest mechanical energy based on contact or sliding electrification [5].

This approach, nevertheless, comes with three problems: firstly, conventional TENG device is often based on solid/solid contact, and it is hard to ensure the contact intimacy of the two tribo-materials [5 p22] . Secondly, the material surfaces will wear or become damaged after long-term friction [5]. Thirdly, the solid/solid-based TENGs need shell structures or mechanical components such as springs, holders, and rotors to harvest random vibration energy [6]. The complex structure will reduce the efficiency of energy harvesting there yielding a better result [7. p11]]

III. TECHNICAL CHALLENGES IN HARNESSING BLUE ENERGY FROM A POWER SYSTEM PERSPECTIVE INCLUDE:

The Membrane Efficiency: Efficient membranes are crucial for osmotic processes like pressure retarded osmosis and its technicalities [4]. Developing high-performance membranes that can withstand harsh conditions and enhance energy conversion is a persistent challenge in the processes of harnessing blue energy [8], [9p5]. This at best will create powerful; reversal process which will retard the system.

The Scale-Up Issues: Scaling up osmotic power generation for practical applications poses engineering and logistical challenges [10]. Achieving cost-effective, large-scale systems while maintaining efficiency remains a hurdle to be achieved due to its complicated nature[10p9].

The Environmental Impact: The discharge of brines or concentrated solutions back into the environment can have ecological and pollution consequences [11]. To minimizing the environmental impact of these discharges requires careful consideration and mitigation strategies that has proven cost intensive over times [12].

Energy Conversion Efficiency: Improving the overall energy conversion efficiency of osmotic power systems is essential in the harnessing of power energy[2p8]. Enhancing the performance of turbines and other components to maximize power output is an ongoing focus of research in today's energy search [5 p13]

The Corrosion and Material Challenges: The harsh conditions presented by saltwater environments due to its high level of salinity which can lead to corrosion and material degradation [7]. Developing corrosion-resistant materials suitable for prolonged exposure is crucial for the longevity of blue energy systems harvesting and utilization.

IV. THE CONTROL OF ENVIRONMENTAL IMPACT IN BLUE ENERGY PRODUCTION:

Controlling the environmental impact in blue energy conversion involves implementing strategies to mitigate potential negative effects [6]. Here are some measures:

Brine Disposal Management: Develop efficient methods for brine disposal to minimize its impact on marine ecosystems. Dilution and dispersion strategies can be employed to reduce the concentration of discharged brine [13].

Selecting Low-Impact Sites: Choose locations for blue energy installations carefully, considering the local ecology and minimizing disruption to sensitive habitats [9p15]. Avoid areas with high biodiversity or where ecosystems are particularly vulnerable to the system [14 p8].

Monitoring and Research: Implement continuous monitoring of environmental parameters in and around blue energy facilities. Conduct ongoing research to understand the long-term effects of brine discharge and other potential environmental impacts

Closed-Loop Systems: Explore closed-loop systems that recirculate the brine internally, reducing the need for direct discharge into the environment [9]. This approach can minimize the impact on surrounding ecosystems and improve the environment.

Environmental Impact Assessments (EIA): Conduct thorough environmental impact assessments (EIAs) before implementing blue energy projects. EIAs help identify potential risks and guide the development of mitigation strategies to protect the environment [7p2].

Stakeholder Engagement: Involve local communities and stakeholders in the planning and decision-making processes. Addressing concerns and obtaining input from those affected can lead to more sustainable and accepted blue energy projects1[5p6].

Reserch on Alternative Materials: Investigate and use materials in blue energy systems that have minimal environmental impact and are resistant to corrosion. This can reduce the risk of pollution from materials used in Open sidebar. Figure 1 shows the triboelectric nanogenerators differentials and its application in blue energy harvesting.

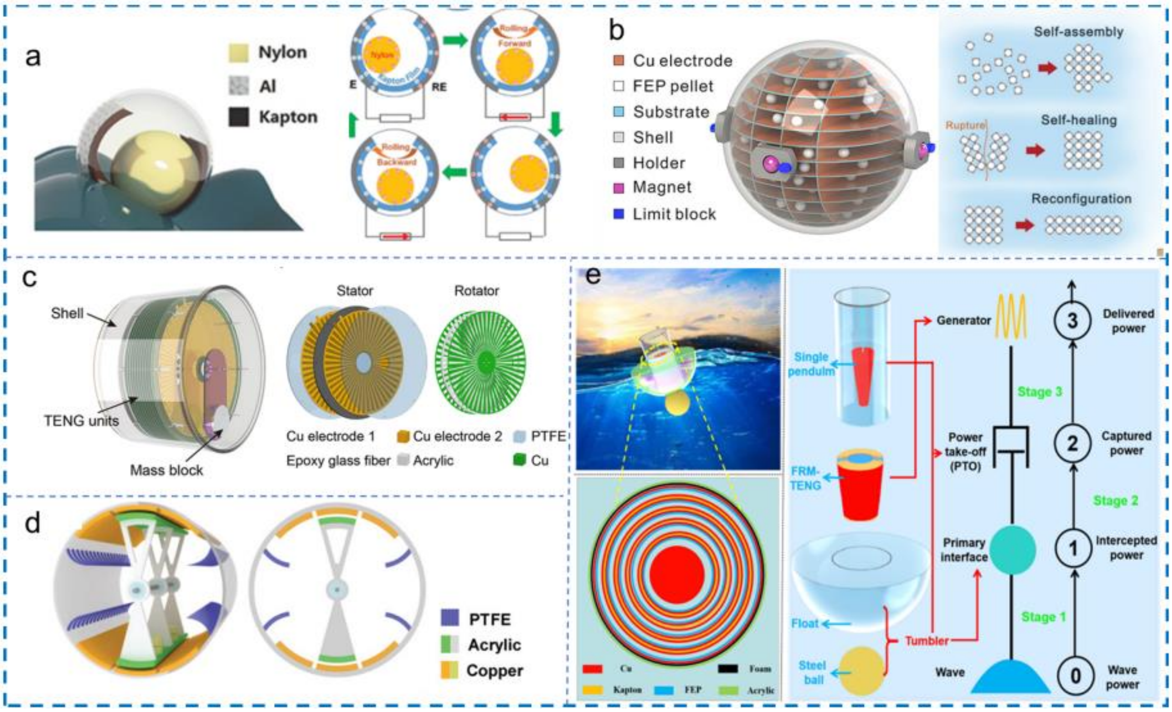

Figure1: The image presents a detailed comparison of different triboelectric nanogenerators (TENGs) and their applications in harvesting blue energy:

Part a: this figure shows the nylon, aluminum and Kapton arrangement in spherical turbo system.

part b: compares the work mechanisms and performance of an EMG (electromagnetic generator) and various TENGs, including their output at low frequency, amplitude, and input power.

Part c: illustrates typical structures of TENGs designed for blue energy harvesting, showcasing diverse designs like spherical, swing-structured, duck-shaped, fur-brush, and active resonance TENGs.

Part d: The figures highlight the materials used in these devices (e.g., Nylon, Al, Kapton, Cu, PTFE, Acrylic, Copper, FEP pellet) and their operational principles, such as self-assembly, self-healing, and reconfiguration in TENG networks.

Part e: The document also provides references for the reproduced content, indicating its origin from various research publications and institutions like Elsevier Ltd., Wiley-VCH Verlag GmbH & Co., KGaA, Weinheim, and Tsinghua University Press.

V. THE ROLE OF BLUE ENERGY IN ADDRESSING GLOBAL ENERGY CHALLENGES;

Blue energy plays a pivotal role in addressing global energy challenges by tapping into the vast potential of oceanic resources [15p3]. Through harnessing tidal and wave energy, as well as exploiting thermal gradients, blue energy provides a sustainable and renewable power source [16]. This approach not only diversifies the energy mix but also contributes to reducing reliance on non-renewable resources while mitigating environmental impact, and fostering a more resilient and environmentally friendly energy landscape on a global scale[14p9]. Figure 2: shows an oceanic water pressure difference which creates the concentration gradient that enables the production of blue energy.

Temperature differences, which naturally occur in the ocean, underpin an emerging green technology.
Photo credit: Ant Rozetsky via Unsplash

Figure 2: Temperature difference of the ocean.

Control of scale up issue blue energy generation:

Scaling up blue energy generation faces challenges that can be addressed through strategic planning and innovative solutions. Implementing modular and flexible designs allows for incremental expansion, minimizing initial infrastructure investments [17]. Additionally, continuous research and development can lead to more efficient technologies, optimizing performance and reducing costs as projects scale [8,7]. Collaborative efforts between governments, industries, non-government institutions and research institutions can streamline regulatory processes by ensuring a supportive framework for large-scale blue energy projects [18]. By proactively addressing these issues, the scalability of blue energy generation can be effectively managed and enhanced [3,5].

Control of membrane efficiency issues in blue energy generation.

Efficiency issues related to membranes in blue energy generate on, particularly in processes like osmotic power generation can be addressed through various strategies [1]. scientific advances in membrane materials with improved selectivity and durability can enhance overall efficiency [9]. Hence regular maintenance and cleaning protocols can prevent fouling by maintaining membrane performance over time. Several researches into innovative membrane technologies such as graphene-based or nanostructured materials may lead to breakthroughs in improving energy conversion efficiency [19]. In addition, optimizing operational parameters and performances like pressure and temperature can contribute to better membrane utilization [19,12]. The continuous research and development efforts aimed at refining membrane technologies are crucial for overcoming efficiency challenges in blue energy generation [7,11].

How corrosion and material damages be mitigated in blue energy generation

Mitigating corrosion and material damages in blue energy generation involves adopting protective measures and selecting appropriate materials. Coating materials with corrosion-resistant layers, such as polymer coatings or corrosion-resistant alloys, can safeguard against corrosive effects of seawater. Regular inspections and maintenance schedules help detect and address potential material issues early on by preventing extensive damage [20]. Employing materials specifically designed for marine environments with high resistance to corrosion and degradation, enhances the overall durability of components [21]. Furthermore, ongoing research into advanced materials and coatings can contribute to the development of more resilient and long-lasting structures in blue energy systems [22].

VI. **BLUE ENERGY:**

Ocean is vitally important for global climate change. A recent report by European Academy of Sciences and Chinese Academy of Sciences [23] shows, "while drastic reduction of the emission of greenhouse gases is urgently needed which includes ocean energy substitution for fossil energy". Ocean is the key for the sustainable development of humankind. The blue energy was first introduced by Wang [23,4] in 2014 that was about the harvesting of ocean water related energy. Much progress has been made in developing various technologies toward blue energy [28–30]. Here, the definition of the blue energy can be further expanded to include all of the energy harvested from water related kinetic and potential energy from ocean and rivers, which include but not limited to hydropower, ocean energy, and offshore energy. More importantly, blue energy also includes the hybrid energy by integrating water energy, water-surface related solar energy, and ocean wind energy as a comprehensive approach toward the sustainable development of humankind.

VII. HYDROPOWER:

SIGNIFICANCE OF DEVELOPING HYDROPOWER:

The global river length has reached 35.9 million km, with a waterflow of 37,411 km3 per year and a maximum drop of 979 m [23,32]. The global river contains over 120 PW·h per year of hydropower, making it uniquely suited for hydropower development [23]. At present, the installed capacity of hydropower is over 1300 GW, and the annual total power generation accounts for more than 16% of the global total power generation [23]. The practical significance of developing hydropower is profound and extensive, mainly reflected in the following aspects:

(1) The optimization of energy structure and sustainable development. With the global emphasis on environmental protection and sustainable development, the extraction and use of traditional fossil fuels are facing increasing restrictions and challenges [24]. As a clean and renewable energy source, the large-scale development and utilization of hydropower can help optimize the energy structure, reduce dependence on fossil fuels, and promote the green and low-carbon transformation of energy [25]. This is of great significance for achieving global climate goals and addressing energy crises for a future assessment [26].

(2) Ecological environment protection and governance. Hydroelectric power generation has significant advantages in reducing pollutant emissions. When compared with fossil fuel power generation, hydroelectric power generation does not produce atmospheric pollutants

such as sulphur dioxide and nitrogen oxides, nor does it produce solid waste such as wastewater and waste residue [27]. In addition, scientific hydropower development can also bring ecological and environmental benefits such as flood control and disaster reduction, soil and water conservation, and improvement of water quality [27-29]. All of these contribute to improving the quality of the ecological environment and enhancing people's living standards [28].

(3) Energy security guarantee. Stable and reliable hydropower generation unaffected by market fluctuations and geopolitical influences is an important means of ensuring national energy security [29]. In case of energy supply shortage or emergencies, hydropower can be used as an emergency power source to ensure the stability and reliability of power supply. This is of great significance for maintaining energy security and ensuring the normal operation of the economy and society [30].

VIII. CURRENT STATUS OF HYDROPOWER:

In recent years, the growth rate of hydropower generation in developing countries has significantly accelerated mainly due to their abundant hydropower resources and rapidly developing economic needs, although the growth rate of hydropower generation in developed countries has significantly slowed down, and they hold a cautious attitude towards hydropower generation [24].

In Asia Pacific region, due to rapid economic development and increasing demand for electricity, the hydropower generation in the Asia Pacific region has significantly increased. Hence, China and India are the main contributors. In Central and South America based on a solid foundation of hydropower resources, the hydropower generation has also achieved steady growth[31]. In Europe, although the overall hydropower generation has declined, some countries such as Norway and Sweden still maintain a high level of hydropower generation [31,11]. In North America, the hydropower generation has also increased, and hydropower projects in countries such as USA and Canada continue to advance [31,4-9]. In Africa and the Middle East, although the proportion of hydropower generation in these regions is relatively low, they have also shown an increasing trend in recent years[31,15]. Figure 3; presents a ranking of the top ten countries in terms of global hydropower generation based on data from the World Energy Statistical Yearbook 2024. They are China, Brazil, Canada, USA, Russia, India, Norway, Vietnam, Japan, and Sweden in that order [32]. Especially, China's annual power generation is far ahead, reaching more than 1300 TW·h, which is three times that of the second ranked Brazil. Challenge; the development of hydropower mainly faces two challenges: environmental impact and social controversy [32,3]. Firstly, hydroelectric power generation may have negative impacts on the natural ecological environment, such as damaging river ecosystems and affecting fish migration [33]]. Therefore, in the planning and construction of hydropower projects, it is necessary to fully consider environmental protection and ecological restoration measures [33]. Secondly, in some countries and regions, hydropower projects may trigger social controversies and conflicts of interest. For example, reservoir construction may lead to issues such as land inundation and relocation of residents [34]. Figure 3 showsthe 2024 global ranking of hydropower generation.

Figure 3: 2024 global Annual hydropower generation.

S/No	**Ranked countries**	**Approximate annual hydro power generation**
1	China	1,222tetrawatt-hour (TWh)
2	Brazil	Over 413 terawatt-hour
3	Canada	341.8million MWh
4	Usa	241billion kilowatt-hours
5	Russia	1385Mwhour*** declined due to war with Ukraine
6	India	134 tetra watt-hour
7	Norway	137974GWh-hour
8	Vietnam	28.63billionkWh
9	Japan	76.82bn kWh

10	Sweden	243tetrajoules
11	Africa	167TWh

Significance of developing ocean energy:

The global ocean area is approximately 360 million km2 containing a huge amount of energy [35]. Ocean energy mainly includes five types: tidal energy, wave energy, temperature difference energy, salt difference energy, and ocean current energy [36]. These energies exist in different forms in the ocean and are unevenly distributed. Tidal energy which refers to the potential and kinetic energy of seawater during the rising and falling tides mainly distributed in coastal areas especially in areas with large tidal amplitudes [36]. The global tidal energy resources are approximately 800 TW·h per year, known as the blue oil fields [35]. Wave energy mainly distributed in the ocean, especially in areas with large waves such as South Pacific and North Atlantic. The global wave energy is up to 8000–80000 TW·h per year, but currently there is only a small installed capacity [35].The breakthrough of wave energy technology has injected new vitality into the development of this field. Temperature difference energy, salt difference energy, and ocean current energy: These types of ocean energy have also been developed to varying degree but compared to tidal and wave energy, their technological maturity may be slightly inferior [35,8]. The development and utilization of ocean energy are very important for alleviating energy crisis and reducing environmental pollution [35,9-10]. Firstly, ocean energy is renewable and inexhaustible providing important guarantees for energy security. Figure 4 shows the relationship between TENG and EMG.

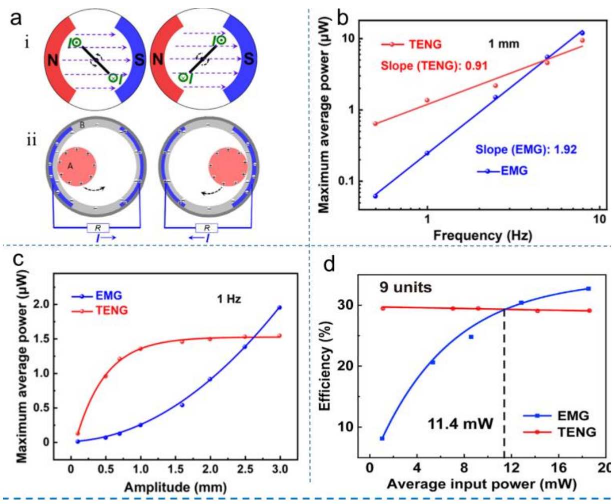

Figure 4: characteristics of TENG and EMG. The image displays the performance characteristics of a Triboelectric Nanogenerator (TENG) and an Electromagnetic Generator (EMG), likely in a hybrid energy harvesting system.

Part (a) illustrates the working principles of both generators: (i) shows a rotational electromagnetic generator with magnets and coils, and (ii) depicts a rotational triboelectric nanogenerator with triboelectric layers.

Part (b). Itcompares the maximum average power output of TENG and EMG as a function of frequency, showing different power dependencies on frequency for each generator.

Part (c) : It compares the maximum average power output of TENG and EMG as a function of amplitude at a fixed frequency of 1 Hz, demonstrating how power varies with displacement for both.

Part (d): This presents the efficiency of TENG and EMG as a function of average input power, indicating that TENG maintains a higher efficiency across a wider range of input power, especially at higher input power levels.

IX. SUMMARY

Blue energy; power derived from the ocean's kinetic, thermal, and chemical resources offers a vast renewable supplement to the global energy mix. The principal technologies that have reached commercial or advanced-prototype stages are:

1.Wave Energy Converters (WECs) Devices that capture the up-and-down motion of surface waves. Common designs include point absorbers (e.g., the "WaveRoller"), oscillating water columns, and attenuators (e.g., the "Pelamis"). WECs benefit from high energy density near coastlines and islands, but they must survive extreme sea states and contend with the variability of wave height and direction.

2. Tidal Stream Turbines – Underwater turbines placed in fast-flowing tidal channels. Similar in principle to wind turbines, they exploit the predictable, high-velocity currents generated by the rise and fall of tides. Projects such as the SeaGen (UK) and the Rime (France) have demonstrated multi-megawatt output, though deployment is limited to sites with sufficient tidal range and flow speed.

3.Tidal Barrage and Lagoon Systems – Large-scale hydraulic structures that impound water during high tide and release it through turbines during low tide. The Rance barrage (France) has operated for decades, providing firm, dispatchable power but at high capital cost and with potential ecological impacts on estuarine ecosystems.

4. Ocean Thermal Energy Conversion (OTEC) – Systems that use temperature differences between warm surface seawater and cold deep water to drive a Rankine cycle. Closed-cycle OTEC plants (e.g., the 1 MW pilot in Hawaii) can provide continuous baseload power, yet

they suffer from low thermal efficiency (3-5 %) and require substantial seawater pumping infrastructure.

5. Salinity Gradient (Blue-Osmotic) Power – Exploits the chemical potential between freshwater and seawater using membranes (pressure-retarded osmosis) or electrochemical cells (reverse electrodialysis). Pilot plants in Norway and the Netherlands have shown promise, but membrane costs and fouling remain barriers.

6. Hybrid and Emerging Concepts – Combinations such as floating offshore wind-wave hybrids, piezoelectric sea-floor generators, and bio-fouling-resistant materials aim to reduce costs and increase reliability.

X. RECOMMENDATIONS FOR FUTURE RESEARCH AND DEVELOPMENT

1. Materials and Corrosion Resilience – Invest in advanced coatings, corrosion-resistant alloys, and bio-fouling mitigation strategies that can extend component lifetimes in the harsh marine environment, thereby lowering levelized cost of electricity (LCOE).

2. Modular, Scalable Designs – Develop standardized, containerized units (e.g., modular WECs or small-scale OTEC modules) that can be rapidly deployed in remote coastal communities, including island nations and offshore Nigerian platforms.

3. Hybrid System Integration – Explore synergistic combinations such as floating wind turbines paired with wave energy converters, or OTEC plants coupled to desalination, to share infrastructure, smooth power output, and improve overall economics.

4. Advanced Control Algorithms – Implement real-time predictive control using AI and sensor networks to optimize power capture from variable wave and tidal conditions, reducing structural stress and increasing capacity factor.

5. Environmental Impact Assessment – Conduct comprehensive, site-specific ecological studies to quantify effects on marine life, sediment transport, and coastal processes, guiding design modifications that minimize habitat disruption.

6. Cost-Reduction through Manufacturing – Adopt additive manufacturing (3D printing) and large-scale offshore assembly techniques to lower fabrication costs and shorten deployment timelines.

7. Grid Integration and Energy Storage – Research cost-effective energy storage solutions (e.g., offshore batteries, hydrogen production) and power-electronics architectures that can handle the intermittent nature of wave and tidal power, ensuring stable grid connection.

8. Policy and Financing Frameworks – Advocate for long-term subsidies, green-bond financing, and risk-guarantee mechanisms tailored to marine energy projects, mirroring

successful models from offshore wind. Through focusing on these research push, the blue-energy sector can move from prototype demonstrations to economically viable, large-scale contributions to the renewable energy portfolio, especially for coastal regions like Nigeria where ocean resources are abundant

Data availability:

Pictures from Elsevier publications. Data extract from 2024 yearly global hydropower report

Use of AI statement:

AI was used to correct the grammatical structures.

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