Market Potential and Sustainability: A Comprehensive Analysis of Marine Renewable Energy Technologies

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Abstract- The global energy transition towards cleaner and more sustainable alternatives is essential for mitigating climate change and enhancing energy security. Marine energy technologies, including offshore wind (OSW), tidal energy (TE), wave energy (WE), ocean thermal energy conversion (OTEC), and salinity gradient power (SGP), offer promising solutions to diversify the renewable energy portfolio and reduce reliance on traditional fossil fuels. This study comprehensively analyses marine energy's technical, environmental, and socio-economic dimensions. Key findings reveal the vast potential of marine energy technologies in addressing global energy challenges. Despite initial hurdles such as high upfront costs and environmental concerns, ongoing technological advancements and concerted global efforts drive increased interest and investment in marine energy projects worldwide. Market analysis underscores the significant role of marine energy in meeting growing electricity demand and providing sustainable solutions for desalination and wastewater treatment. Consumer perception and adoption patterns play a crucial role in shaping the future trajectory of marine energy technologies. Effective marketing and communication strategies are essential for fostering greater acceptance and adoption in the energy market. Economic viability analysis highlights job creation and infrastructure investment potential supported by government policies and incentives. Stakeholder engagement emerges as a critical determinant of success in the marine energy sector, emphasizing the importance of collaboration among businesses, policymakers, and local communities. Embracing the vast potential of ocean-based energy sources is imperative for navigating towards a cleaner, more resilient energy future. Continued research, investment, and collaboration are essential to unlocking the full potential of marine energy and ensuring a sustainable energy transition.

Keywords Marine renewable energy (MRE), sustainable energy market, environmental impact assessment, economic feasibility, social acceptance.

1. Introduction

Technological developments, regulatory initiatives, economic considerations, and environmental concerns are driving the global shift away from fossil fuels and toward sustainable alternatives. [1]. This energy shift aims to address climate change and improve energy security by utilizing renewable sources that provide electricity without emitting greenhouse gases [2]. In addition to addressing environmental concerns, the shift provides significant economic benefits such as cost competitiveness, job development, economic growth, and less reliance on foreign fuels. Decentralized deployment of renewable energy empowers local populations and promotes energy democratization [3].

Furthermore, the energy shift provides opportunities for innovation and technical improvement in energy storage, grid integration, efficiency, and electrification [4]. This integration reduces costs and enhances energy systems' reliability, resilience, and flexibility. Despite the promise of renewable sources, challenges such as intermittency and variability necessitate strategic investments in energy storage technologies, grid modernization, demand-side management, and flexible power generation [5]. The potential economic dislocation in fossil fuel-dependent industries underscores the need for comprehensive strategies, including retraining programs, economic diversification, and investments in renewable energy [6].

Transitioning to renewable energy is crucial for reducing climate change, ensuring energy security, and promoting sustainable economic growth [7, 8]. Adopting low-emission renewable sources significantly reduces the carbon footprint, preserving the planet's health and ensuring future generations' well-being. Notably, renewable energy technologies, such as solar panels, wind turbines, and hydroelectric dams, have a minimal environmental impact compared to traditional fossil fuels, reducing air and water pollution, habitat destruction, and conservation of water resources [9].

In addition to environmental benefits, renewable energy enhances energy security by reducing reliance on imported fuels and diversifying the energy mix, thereby increasing resilience to external shocks [10]. The economic advantages, including job creation, growth, and innovation, make renewable energy an attractive investment. Skilled manufacturing, installation, maintenance, and research workers contribute to a thriving industry, while cost competitiveness attracts investment and stimulates innovation in new technologies [11]. The global transition to renewable energy sources marks a crucial step toward building a sustainable, resilient, and equitable alternative to finite fossil fuels.

The Electricity Market Report 2023, published by the International Energy Agency (IEA), shows in Figure 1 the annual electricity generation changes by energy source and the forecasts for the next two years. The report suggests that from 2023 to 2025, renewable energy generation could grow at more than 9% annually, exceeding the growth in other sources. In 2025, renewables could supply more than one-third of the world's electricity. Combined, low-carbon renewables and nuclear power are projected to have the potential to supply more than 90% of additional electricity demand over the next three years [12]. Still, these trends could be affected by global economic conditions and weather events.

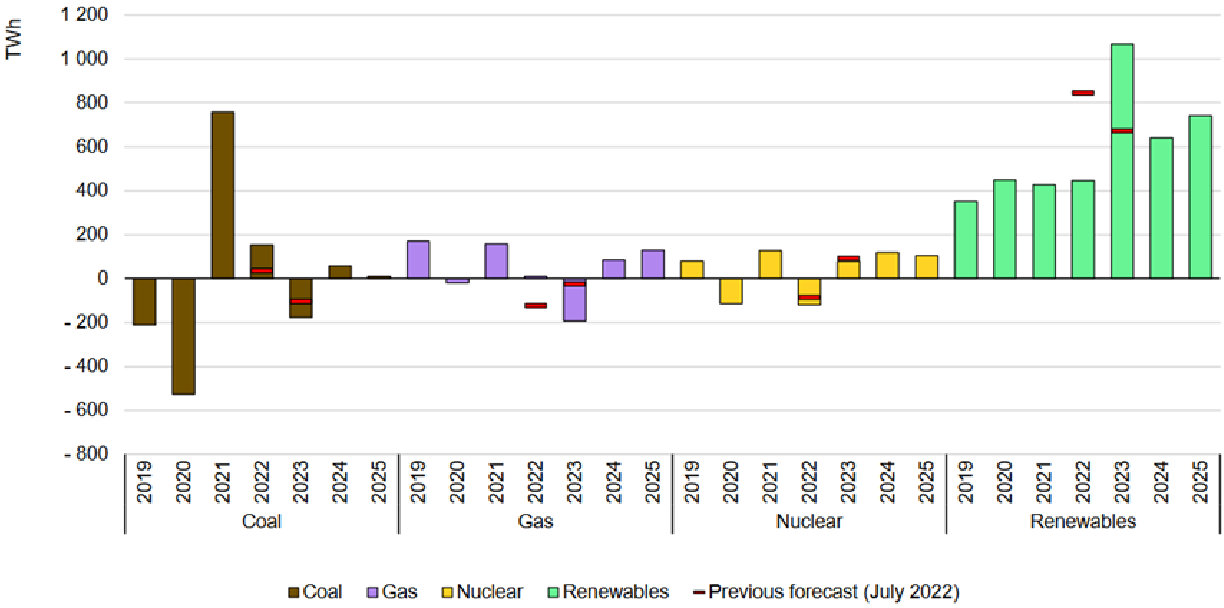

Fig. 1. Year-on-year global change in electricity generation by source, 2019-2025 [12].

The potential of marine renewable energy (MRE) technology to address the global demand for sustainable and environmentally friendly energy while contributing to the economic progress of coastal regions is substantial. Nearly 70% of the Earth's surface is occupied by oceans and seas; therefore, MREs are abundant, broadly accessible, consistent, and predictable for off-grid and on-grid electricity generation globally, especially for off-grid coastal communities [13-15]. Research on MRE has experienced significant growth and commercialization since 2008. MREs have the potential to supply nearly one million jobs and satisfy about seven percent of the world's electricity demand by 2050 [16]. Offshore, floating solar, and OSW energy sources are the most prevalent because of their affordability and research maturity. Nevertheless, the intermittent and climate-dependent characteristics of these energy sources impose constraints on the dependability of the energy provision. The potential of MRE conversion into electricity to meet a substantial portion of the world's energy demand has refocused the attention of scientists on this topic. As illustrated in Figure 2 [17-19], MRE varieties consist of floating solar, offshore windmills, tidal flow, wave, OTEC, salinity gradient, pressure retarded osmosis (PRO), and underwater turbines, among others.

Marine energy is crucial in addressing multifaceted global challenges encompassing climate change, environmental degradation, energy security, and economic development, especially in regions with limited access to conventional energy [20]. Tapping into the potential of tidal and WE sources, particularly in regions with robust tidal currents and consistent wave patterns, involves deploying innovative technologies such as tidal turbines and WE converters [21]. Additionally, OTEC harnesses the temperature differentials in tropical regions, offering the potential for baseload power [22]. Meanwhile, marine current energy exploits ocean currents like the Gulf Stream, providing a reliable and consistent energy source for coastal communities [23].

Despite the promise, marine energy faces barriers such as high costs, uncertainties, regulatory complexities, and environmental concerns stemming from harsh marine environments and engineering challenges [24]. However, global efforts to combat climate change and technological advancements propel interest in marine energy projects, leading to collaborations between governments, research institutions, and private companies to develop solutions, enhance performance, and reduce costs [25]. Marine resources, encompassing TE, WE, OTEC, and marine current energy, offer a diverse technological landscape, providing deployment flexibility and leveraging coastal regions' unique characteristics for power generation [26]. Their reliable and predictable nature, dictated by tides, wave patterns, and ocean temperatures, positions marine resources as an attractive option for meeting electricity demand.

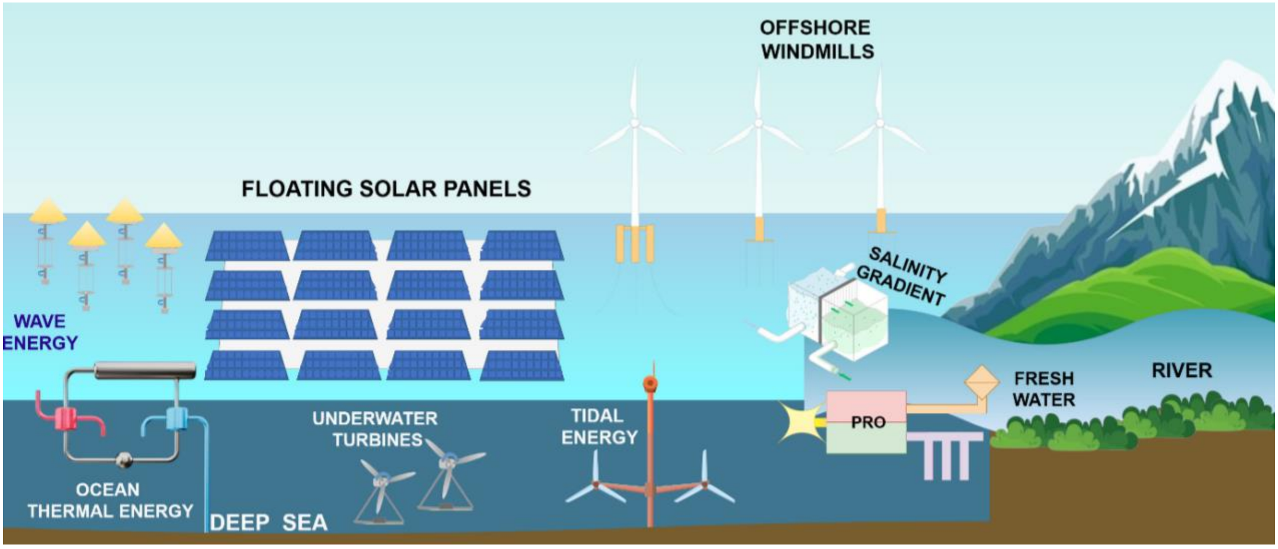

Fig. 2. MREs' representative diagram

The potential of marine energy extends beyond climate mitigation, offering local economic opportunities and supporting sustainable development in coastal regions and island nations [27]. Contributing to a low-carbon economy and long-term climate goals, responsible deployment of marine energy technologies provides environmental benefits with minimal impact on marine ecosystems [28, 29]. FSPs, OSW, TE, SGP, and underwater turbines form part of this diverse marine energy landscape [30]. However, challenges such as disruption to aquatic ecosystems by OSW farms, navigation hazards from WE devices, and high project costs hinder widespread adoption [31, 32]. Grid integration challenges stemming from the intermittent nature of wave and TE necessitate complementary solutions like energy storage, demand management, and ongoing research [33].

The European Commission is a leader in ocean energy research and development through its investments. Figure 3 shows the sectoral percentages of MRE invested by the European Commission. Over the last decade, the United States has also provided R&D funding to support the ocean energy sector [14].

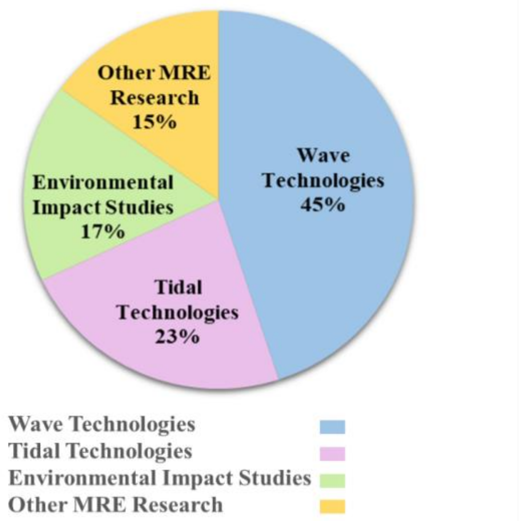

Fig. 3. Sectoral Distribution of MRE Investments by the European Energy Commission [14]

Marine resources offer a sustainable solution to global challenges, providing environmental, economic, and social benefits. OSW, tidal currents, WE, and OTEC hold immense potential for electricity generation, job creation, and economic development. At the same time, responsible sitting, environmental assessments, and monitoring are imperative to preserving marine ecosystems and biodiversity. By embracing the potential of ocean-based energy sources and adhering to sustainability principles, nations can navigate towards a cleaner, more resilient energy future, addressing climate change, energy security, and socioeconomic development.

Marine energy reviews are instrumental in elucidating the viability, potential, and challenges of harnessing marine resources. Serving as a compass for decision-making, research gap identification, and future funding direction, these reviews establish a foundation for public awareness and technological advancements. An important study investigated the interaction between MRE devices and the marine environment, revealing no significant adverse effects on marine life from underwater noise emissions, electromagnetic fields, or habitat changes [35]. Another study introduced a risk retirement process, streamlining environmental risk assessments in the MRE industry and developing sustainability [36]. Addressing biofouling challenges, [37] developed a European biofouling database, supporting informed decisions, optimizing device performance, and contributing to sustainable MRE growth. Another study explored the legal landscape around MRE projects, emphasizing the role of marine planning policies and successful case studies in Ireland, Portugal, and the UK [38]. Changing to grid applications, [39] highlighted the temporal qualities of MRE resources, offering insights for policymakers and energy planners to enhance grid stability. Lastly, [40] conducted a comprehensive study on MRE's global power capacity, emphasizing the need to balance energy production, resource investment, and environmental impacts. These studies offer a roadmap for sustainable growth, providing valuable insights for advancing marine energy technologies and developing a greener energy future.

In this comprehensive study, we search into the multifaceted landscape of MRE, exploring various technologies such as OSW, TE, WE, OTEC, and SGP. Our research is strategically designed to unravel these marine energy sources' potential applications and technological intricacies and dissect their distinct advantages, disadvantages, environmental impacts, economic performances, and social acceptance considerations. This multidimensional analysis is a foundational framework for investigating marine energy's business and marketing aspects. By intertwining renewable energy technologies with the nuances of consumer behavior and marketing communication, our research addresses critical questions surrounding the viability, marketability, and societal acceptance of these innovative energy solutions. Through this interdisciplinary approach, we endeavour to uncover insights that bridge the gap between sustainable technologies and the dynamic landscape of consumer preferences and market dynamics. This study sets out to contribute valuable perspectives to business, marketing, and consumer behavior within the context of emerging marine energy technologies.

The potential applications, the advantages and disadvantages, the environmental impact, the economic performance compared to other renewable energy sources, and how it is perceived and accepted socially will be questioned for OSW, TE, WE, OTEC, and SGP. By addressing these questions, the findings sections provide a comprehensive overview of each MRE source, covering their applications, advantages, disadvantages, environmental impacts, economic performances, and social acceptance considerations.

In the context of MRE technologies, this study's evolutionary research approach provides a foundational framework for examining technologies' intricate and evolving landscape in the global energy market. It allows for identifying pivotal innovations, selection mechanisms, and preservation strategies that impact the adoption and commercialization of MRE technologies. Moreover, the evolutionary research approach facilitates a thorough investigation into the market viability of marine renewable energies, which is a valuable perspective for understanding the interaction between technology advancement, market dynamics, and sustainability objectives.

The study significantly contributes to advancing knowledge in MRE by thoroughly analyzing various aspects related to different types of marine energy sources. The study examines diverse MRE sources, including OSW, TE, WE, OTEC, and SGP. This comprehensive overview consolidates existing knowledge and is a valuable resource for researchers, policymakers, and practitioners. The study goes beyond a simple description of marine energy sources by conducting a multidimensional analysis. The research provides a holistic understanding by exploring potential applications, advantages, disadvantages, environmental impacts, economic performances, and social acceptance considerations for each type of marine energy. This multidimensional approach contributes to a more nuanced and informed decision-making process. The study identifies specific challenges, such as high upfront costs, environmental impacts, and social acceptance issues, through the detailed analysis of each marine energy source. Simultaneously, it highlights opportunities, including economic benefits, job creation, and contributions to sustainable development. Identifying challenges and opportunities guides future research, policy development, and industry strategies. The study underscores the role of MRE in the broader context of sustainable energy transition. By emphasizing the potential for reducing greenhouse gas emissions, mitigating climate change, and promoting energy security, the research positions marine energy as a crucial player in global efforts towards cleaner and more resilient energy systems. Through discussions on economic performance and social acceptance, the study provides insights into the role of policies and regulatory frameworks. By recognizing the influence of government incentives, tariffs, and stable regulatory environments, the research contributes valuable knowledge to policymakers and regulatory bodies aiming to build the growth of marine energy technologies. By acknowledging current technological advancements and ongoing research efforts, the study suggests future directions for research and development in the field. By identifying areas such as environmental impact mitigation, cost reduction, and technological innovation, the research contributes to the roadmap for advancing marine energy technologies.

2. Methodology

This comprehensive study employs an Evolutionary Research Method, a specialized subset of qualitative research, to investigate the multifaceted landscape of Marine Renewable Energy (MRE) technologies, including Floating Solar Panels (FSPs), Offshore Wind (OSW), Tidal Energy (TE), Wave Energy (WE), Ocean Thermal Energy Conversion (OTEC), and Salinity Gradient Power (SGP). The evolutionary research method offers a unique perspective on the historical evolution and progression of ideas, technologies, and concepts, drawing on principles such as natural selection and adaptability [41].

The evolutionary research method is analogous to biological processes, where ideas or technologies undergo divergent selection and retention phases. New variations emerge as innovative concepts or technological iterations surface, with selection processes determining their suitability for adoption and widespread use [42].

Embedded within the broader qualitative research framework, this method is invaluable in fields requiring a deep understanding of evolutionary trajectories and offering a dynamic view of ongoing evolutionary processes [43].

The study strategically examines various MRE technologies' potential applications and technological intricacies, aiming to dissect their distinct advantages, disadvantages, environmental impacts, economic performances, and social acceptance considerations. This research approach allows for a comprehensive understanding of the complex interactions inherent in MRE projects, involving diverse stakeholders such as policymakers, industry representatives, environmental advocates, and local communities.

The methodology involves a systematic review of relevant literature published from 2020 onwards, focusing on studies that provide insights into the technological advancements, market dynamics, and socio-economic factors shaping the MRE landscape. Key themes and findings from the literature are emphasized and interpreted in the context of this study's research objectives.

The findings section provides comprehensive explanations for each MRE technology under the subheadings of Potential Applications, Advantages & Disadvantages, Environmental Impact, Economic Performance, and Social Acceptance.

These findings are further discussed in the subsequent sections, including opportunities and challenges for the energy market, consumer perception and adoption, marketing and communication strategies, economic viability and investment, stakeholder engagement, and a comparative analysis of MRE technologies. This methodologically rigorous approach aims to contribute valuable insights into the ongoing development and expansion of the MRE sector, providing a holistic understanding of its multifaceted challenges and opportunities.

3. Findings

3.1. Floating Solar Panels

3.1.1. Potential applications

FSPs, or floating photovoltaic systems, offer a sustainable and versatile way to harness solar energy, particularly in renewable energy generation. By deploying solar panels on water bodies, FSPs minimize land-intensive installations, address land scarcity, and enhance energy efficiency by reducing water heat absorption, lowering panel temperatures, and improving electricity output. [44]. FSPs enhance energy sustainability in water-intensive industries by generating energy from reservoirs and wastewater treatment ponds, reducing evaporation rates, and conserving water resources. FSPs can power irrigation systems in agriculture and support sustainable practices in aquaculture ponds [45]. FSPs can be integrated into hydropower infrastructure, enhancing energy output, grid stability, land and water use efficiency, and minimizing environmental impact by integrating float solar arrays into existing reservoirs. [46]. FSPs can be crucial in addressing energy needs in remote or off-grid areas. Many remote regions lack access to reliable electricity due to their geographical isolation or limited infrastructure. Renewable energy can be generated locally by deploying floating solar installations on bodies of water near these communities, reducing dependence on expensive and environmentally harmful diesel generators. Aside from enhancing energy access, this approach also promotes sustainable development and resilience to the impacts of climate change. The versatility of FSPs extends beyond energy generation to include environmental and ecological benefits. By covering water surfaces, floating solar arrays can reduce the growth of algae and aquatic weeds, improve water quality, and provide shade, creating habitats for aquatic species. Besides, installing FSPs can help mitigate the impacts of climate change by reducing water evaporation, controlling algae blooms, and minimizing thermal pollution in water bodies [46].

3.1.2. Advantages & disadvantages

FSPs optimize land use, enabling dual use of land and water for solar energy production, especially in densely populated areas with limited land resources. This benefits countries with abundant water bodies. [47]. FSPs offer increased efficiency and performance due to water’s cooling effect and natural sunlight reflection, achieving higher energy production than traditional land-based solar installations in hot climate regions. [48]. FSPs offer environmental benefits by reducing evaporation, algae growth, and water loss, improving water quality and biodiversity, and reducing transmission losses and land degradation associated with long-distance electricity transmission in urban areas. [49]. FSPs, despite their advantages, have drawbacks, including higher initial installation costs, complex engineering and construction requirements, and higher maintenance and operational costs due to factors like corrosion, biofouling, and specialized equipment and personnel [50]. FSPs offer water conservation and quality improvement, but their installation can have negative ecological consequences. If not properly managed, they can reduce light penetration, disrupt ecosystems, and pose pollution and habitat degradation risks [51]. Floating PV systems face technical challenges in stability, durability, and performance optimization due to environmental factors like wind, waves, currents, and water level fluctuations. Optimizing orientation and layout for optimal sunlight exposure and energy yield requires careful planning [52].

3.1.3. Environmental impact

FSPs, despite their environmental benefits, have significant environmental impacts. It can alter aquatic ecosystem dynamics by reducing light penetration, potentially affecting photosynthesis and species composition. This could also inhibit submerged marine vegetation growth, which is crucial for aquatic organisms like fish and invertebrates [53]. FSPs can cause water temperature and thermal stratification changes, affecting aquatic organisms' health and survival. This can lead to decreased heating of the water surface, disrupting thermal stratification patterns and exacerbating water quality issues like hypoxia and eutrophication in shallow water bodies [54]. FSP installation and operation can impact water quality and nutrient cycling. Debris accumulation, sedimentation, and biofouling can introduce pollutants, leading to nutrient enrichment and algal blooms. Construction materials may leach harmful chemicals, posing risks to aquatic life and water quality [50]. The deployment of FSPs could alter local hydrology, affecting water flow patterns, sediment transport, and migration patterns of aquatic species. Additionally, the anchoring and mooring systems could cause habitat loss and fragmentation in sensitive marine environments [55].

3.1.4. Economic performance

The economic performance of floating solar projects is influenced by installation costs, operational expenses, energy production, revenue generation, and return on investment. Despite higher upfront costs, technological advancements and economies of scale are reducing the cost gap [44]. Operational expenses of FSPs, including maintenance, monitoring, and repair, are influenced by factors like water quality, environmental conditions, and accessibility. Innovations aim to minimize costs and maximize efficiency [56]. FSPs have economic feasibility due to their energy production potential, which can be enhanced by water-cooling, increased sunlight reflection, and optimal panel orientation, leading to higher energy yields and improved capacity in specific locations [57]. Floating solar projects generate revenue from electricity sales, with economic viability influenced by tariffs, renewable energy incentives, and market demand. Governments, utilities, and private entities can promote projects through financial incentives and innovative financing [58]. Factors like project lifespan, discount rates, inflation, tax implications, and risk factors influence the return on investment in floating solar projects. Despite higher initial capital expenditure, long-term economic returns include lower land costs, increased energy production, operational efficiencies, and revenue streams [59].

3.1.5. Social acceptance

Social acceptance of FSPs depends on public perception, community engagement, cultural considerations, and stakeholder involvement. The perceived visual impact of FSPs can affect acceptance, especially in scenic or culturally significant areas. Community outreach, visual simulations, and view integration measures can address concerns and promote FSPs' environmental benefits and minimal footprint [59]. The construction of floating solar installations may disrupt recreational activities and livelihoods, leading to concerns about access restrictions, noise pollution, and economic impacts. Mitigation measures like buffer zones and ecotourism initiatives can help alleviate these concerns [60]. Floating solar installations can positively impact social acceptance by creating jobs, enhancing local economic development, and improving infrastructure. Clean energy access can alleviate poverty in remote areas. Transparent communication and stakeholder engagement are crucial for trust and positive outcomes [61].

3.2. Offshore Windmills

3.2.1. Potential applications

OSW are robust, consistent wind resources that can be harnessed for various applications, including electricity generation. These farms can generate large amounts of renewable electricity at higher wind speeds, contributing to cleaner, more sustainable energy sources and reducing greenhouse gas emissions [62]. OSW turbines can power offshore installations and facilities in remote locations, providing renewable energy and reducing reliance on fossil fuels, thereby reducing operating costs, carbon footprint, and environmental impact [63]. OSW farms can create renewable energy hubs and green ecosystems by strategically clustering wind turbines. These hubs can integrate wind energy with other renewable sources, enhancing energy security and meeting diverse energy demands [64]. OSW farms can enhance marine biodiversity and support ecosystem services, contributing to conservation efforts. They can also coexist with offshore aquaculture operations, providing stable platforms for aquaculture facilities and leveraging renewable energy production synergies [65]. OSW turbines offer engineering, renewable energy technology, and environmental monitoring innovation and research opportunities. Advanced solutions for harsh marine conditions, reduced costs, and improved efficiency can drive advancements. OSW farms also serve as platforms for scientific research and ocean monitoring [66].

3.2.2. Advantages & disadvantages

OSW offers advantages such as higher energy generation potential due to stronger, consistent wind speeds and mitigating visual and noise impacts on populated areas, thereby contributing to renewable energy targets [67]. OSW farms can diversify energy sources, reduce fossil fuel dependence, and mitigate climate change. They offer scalability for large projects and are becoming cost-competitive with conventional energy sources, making them a sustainable solution [68]. OSW offers advantages like cost-effectiveness but also faces challenges like high initial capital investment, technical complexity, and government subsidies, which can deter investment and hinder economic viability [69]. Offshore farms face logistical challenges in maintenance and operation due to remote locations, costly repairs, specialized equipment access, and harsh marine environments affecting equipment longevity and reliability [70]. While reducing greenhouse gas emissions, OSW farms can negatively impact marine ecosystems, causing habitat disturbance, changes in seabed dynamics, underwater noise disruption, and risks to marine mammals and fish populations [71].

3.2.3. Environmental impact

OSW can potentially reduce climate change and fossil fuel reliance, but it also poses environmental concerns. Disruptions during installation can disrupt marine habitats, potentially affecting species distribution and biodiversity, necessitating careful management [72]. The underwater noise of OSW turbines can negatively impact marine life, including whales and dolphins, causing behavioral changes, habitat displacement, and reproductive impacts. Mitigation measures like acoustic monitoring and construction timing restrictions are used, but effectiveness varies depending on species and habitat [73]. Underwater cables for electricity transmission can disrupt marine environments, affecting nutrient cycling, sediment stability, and benthic habitats. OSW infrastructure may create artificial reefs, alter biodiversity, and accumulate marine debris on underwater structures, impacting benthic communities and substrate habitats [74, 75]. OSW turbines pose a potential collision risk with birds, especially during the migration or high avian activity. While generally lower than onshore installations, certain species like seabirds and waterfowl may be at greater risk [76]. OSW farms' manufacturing, installation, and decommissioning phases involve energy and resource inputs, resulting in greenhouse gas emissions and environmental impacts. Proper lifecycle assessments and environmental management practices are crucial for sustainability [77].

3.2.4. Economic performance

OSW farms require significant upfront capital investment for turbine design, construction, and installation, often higher than onshore wind farms due to technical challenges and logistical complexities, such as deeper water depths and longer transmission distances [78]. OSW offers economic advantages over onshore wind due to its higher capacity factors, resulting in more consistent electricity generation and revenue potential, making it an attractive investment for developers and operators [79]. Advanced technology and design of OSW turbines have led to economies of scale, reducing construction and installation costs. These turbines also improve energy efficiency, reliability, and cost-effectiveness, enhancing the economic viability of OSW energy [80-81]. OSW projects benefit local economies through job creation, supply chain development, and infrastructure investment. Skilled workforces in engineering, construction, maintenance, and logistics stimulate growth. Establishing manufacturing facilities and research centers supports long-term development [82]. OSW projects generate income through electricity sales to utilities and power purchase agreements, with government incentives and subsidies supporting financing. As technology matures, the levelized energy cost for OSW energy is expected to decline [58], [83]. OSW projects face economic challenges like regulatory issues, grid connection costs, financing risks, and market price volatility. Delays, technical issues, and fluctuations in electricity, fuel, and renewable energy policies can impact project timelines and financial returns [67], [84].

3.2.5. Social acceptance

Social acceptance of OSW is influenced by societal values, perceptions, and concerns, affecting communities' and stakeholders' acceptance of this crucial component for sustainable energy transition [85]. Social acceptance of OSW depends on their perceived impact on local communities and stakeholders. While OSWs are often far from shorelines, aesthetic concerns and potential impacts on recreational activities can still influence acceptance [86]. OSW energy projects can stimulate economic growth and create jobs, particularly in coastal regions. These projects can support local industries and critical coastal communities. Revenue-sharing mechanisms, community benefit agreements, and local procurement requirements can further enhance these benefits [87]. OSW farms pose environmental concerns, risks, and competing interests. Addressing these concerns through robust assessments, monitoring programs, and mitigation measures is crucial for building confidence and securing social acceptance [88]. OSW development's regulatory frameworks can influence social acceptance by shaping decision-making processes, stakeholder engagement, and benefit distribution. Transparent, inclusive decision-making, public participation, and education about benefits and trade-offs empower communities to make informed decisions [89].

3.3. Tidal energy

3.3.1. Potential applications

TE from ocean tides can be used to generate electricity in tidal streams and barrage systems. Tidal stream systems use underwater turbines to capture kinetic energy, while barrage systems build dams across estuaries. These renewable energy sources offer a consistent, predictable source, reducing dependence on fossil fuels and mitigating greenhouse gas emissions [90]. TE can enhance grid stability and energy security by providing predictable tidal patterns that balance supply and demand. Integrating TE into the energy mix reduces reliance on imported fossil fuels and mitigates risks [91]. TE can be used for electricity generation, desalination, and water pumping, particularly in coastal regions with limited freshwater access. It can promote sustainable agricultural practices by reducing reliance on fossil fuel-powered pumps [92]. TE systems provide reliable energy for offshore activities like aquaculture and offshore platform operations, improving productivity and efficiency. They reduce diesel generator use, lower operational costs, minimize environmental impact, and reduce operating costs [93]. Developing and deploying TE technologies can stimulate economic growth and job creation by investing in research, manufacturing, installation, and maintenance. This growth attracts investment, supports innovation, and supports supply chain activities, addressing climate change, energy security, and economic development [94].

3.3.2. Advantages & disadvantages

Tides are a renewable energy source with predictability, enhancing grid stability and integrating into existing systems. It contributes to climate change mitigation and air quality improvement, aligning with global efforts towards low-carbon energy. TE projects can have long operational lifetimes, providing a stable, reliable source of electricity over time with proper maintenance [95]. TE projects face high costs, limited availability of suitable sites, and environmental impacts due to their potential to disrupt marine ecosystems and natural habitats [96]. TE generation faces challenges due to intermittency and variability, requiring backup systems and specialized equipment for maintenance in harsh marine environments. This variability challenges matching supply with demand and ensuring reliable electricity supply [97-98].

3.3.3. Environmental impact

Projects such as tidal barrages and turbines can disrupt marine ecosystems and habitats, potentially affecting marine biodiversity and ecosystem functioning. This necessitates comprehensive environmental impact assessments and mitigation measures to minimize adverse effects on local ecosystems and biodiversity, ensuring sustainable development [99]. Tidal turbine projects generate underwater noise and electromagnetic fields, potentially disturbing marine life and causing stress or injury. These noises can interfere with communication, navigation, and feeding behaviors, while electromagnetic fields can affect the behavior of marine organisms, a subject of ongoing research [100]. Tidal barrages and turbine arrays can alter sediment transport, erosion, and patterns in coastal and marine environments, affecting nearshore habitats. Careful site selection, design, and monitoring are crucial to minimize coastal and habitat impacts associated with TE development [101].

3.3.4. Economic performance

Capital costs, operational expenses, revenue streams, and policy support mechanisms influence the economic performance of TE projects. Despite high initial costs, TE projects offer low operating costs compared to conventional fossil fuel-based power generation due to minimal fuel inputs and maintenance requirements [95]. The economic viability of TE projects relies on their ability to generate revenue through electricity sales or other income streams, influenced by factors like energy yield, electricity market prices, grid connection costs, and government incentives. Some projects may also benefit from ancillary services [102,103]. Government policies and regulatory frameworks significantly influence the economic outlook for TE development. Financial incentives, tariffs, tax credits, and certificates offset upfront costs, improving competitiveness. Stable, predictable regulatory frameworks attract private investment and create a conducive environment. [104,105]. The projects face financial challenges due to the limited availability of suitable tidal sites, which can be costly and time-consuming. Variability in TE generation also poses difficulties for revenue forecasting and grid integration, potentially necessitating additional investment in energy storage, grid infrastructure, or backup generation [106,107].

3.3.5. Social acceptance

Public perceptions, community engagement, stakeholder involvement, and socio-economic context influence social acceptance of renewable energy (TE) development. Environmental and ecological impacts, such as habitat disturbance and marine wildlife impacts, can lead to opposition. Addressing these concerns through comprehensive assessments, mitigation measures, and monitoring programs is crucial for building trust and maximizing ecological benefits [108,109]. Community engagement and stakeholder involvement are essential for securing social acceptance of TE projects. By involving stakeholders early in the project lifecycle, developers can build relationships, dialogue, and co-create solutions, while transparent communication raises awareness and supports renewable energy transition [110,111]. The socioeconomic context of project areas significantly influences social acceptance of technology-enhanced Enhanced Education development. Communities facing economic challenges may view TE projects as opportunities for job creation, economic development, and local investment, enhancing social acceptance and reducing disparities [112].

3.4. Harnessing Ocean Waves for Electricity

3.4.1. Potential applications

HOWE, a technology that harnesses ocean WE, has potential applications in renewable energy generation, environmental conservation, and coastal infrastructure development, diversifying the energy mix, reducing fossil fuel reliance, and combating climate change [113]. WE technologies can improve energy security by reducing dependence on imported fuels and supply chains, especially for island nations and remote coastal communities [114]. Ocean waves can be harnessed for desalination, a crucial process in addressing water scarcity in arid coastal regions. This sustainable and cost-effective method secures freshwater supplies, promotes socio-economic development, and mitigates the impacts of climate change [115]. WE infrastructure deployment boosts coastal economies by creating jobs and attracting investment. It requires a skilled workforce, stimulating local activity and supporting industries like engineering, manufacturing, and marine services [116]. WE is a clean, renewable alternative to fossil fuels, reducing greenhouse gas emissions, conserving resources and protecting marine ecosystems from climate change and offshore drilling activities [117]. Integrating WE infrastructure with coastal protection measures enhances resilience to climate change-induced erosion and flooding, reducing vulnerability and generating sustainable electricity [118].

3.4.2. Advantages & disadvantages

Ocean waves offer a promising renewable energy source due to their consistent and abundant nature, lack of seasonal variations, and high energy densities. This makes them suitable for various applications, from small remote communities to large-scale grid integration [119]. Another advantage lies in the predictability of ocean waves. Advanced forecasting techniques allow for accurate predictions of wave patterns, enabling efficient planning and operation of WE systems. This predictability can help integrate WE into existing power grids more effectively, providing a stable and dependable source of electricity [120]. It has minimal environmental impact compared to some other forms of energy generation. WECs typically produce no direct greenhouse gas emissions or air pollutants during operation, contributing to mitigating climate change and reducing air pollution. Besides, WE projects can create artificial reefs, provide habitat for marine life, and potentially enhance local biodiversity [121]. There are also several challenges and disadvantages associated with HOWE. One is the variability of WE. While waves are more predictable than other renewable sources, they can still fluctuate due to weather patterns and seasonal changes. This variability can pose challenges for grid integration and may require additional energy storage or backup systems to ensure a stable electricity supply [122].

3.4.3. Environmental impact

Renewable energy sources like WECs have potential environmental impacts, including disruption to marine ecosystems due to changes in habitats, sediment transport, and species distribution, potentially causing disturbances in feeding, breeding, and migration patterns [123]. WE infrastructure construction can cause physical disturbances to the seabed and coastal areas, impacting benthic habitats like coral reefs and seagrass beds, increasing turbidity, smothering organisms, and altering water quality [124]. WE projects can cause underwater noise pollution, disrupt marine life, cause physiological stress, reduce reproductive success, and disrupt communication, navigation, and feeding behaviors [125]. WE infrastructure, including floating devices, poses risks to marine life, increasing collisions with vulnerable species like sea turtles and seabirds, potentially leading to injury or mortality [126]. Deployment of WECs may pose risks of marine pollution. While WE is a clean and renewable energy source, the materials used in constructing and operating WE devices could potentially leak pollutants into the marine environment. These pollutants may include heavy metals, lubricants, hydraulic fluids, and other chemicals, harming marine organisms and ecosystems [127].

3.4.4. Economic performance

The economic performance of WE is evaluated by examining factors like capital costs, operational expenses, revenue generation, and competitiveness. Initial investment in WE technology, including research, design, manufacturing, installation, and grid connection, has historically been high compared to other renewable energy technologies [128]. Operational expenses of WE projects, including maintenance, monitoring, and repair, are crucial for their economic performance. Offshore maintenance can be challenging due to harsh marine environments, but technological advancements could reduce costs [129]. WE projects generate revenue through production capacity, efficiency and market price. They sell electricity to utilities. The levelized cost of electricity is a crucial metric for assessing competitiveness. Technological advancements and economies of scale are expected to improve cost-effectiveness and competitiveness [130].

3.4.5. Social acceptance

Social acceptance of WE is a complex issue, with positive sentiment towards renewable energy sources like WE for reducing greenhouse gas emissions and promoting energy independence. The ocean’s vast energy potential can inspire enthusiasm for sustainable energy solutions [131]. Projects’ impact on local communities depends on perceived benefits, potential impacts, and stakeholder engagement. Addressing concerns about WE devices, marine ecosystems, noise pollution, and recreational activities is crucial for trust and social acceptance [132]. The socioeconomic benefits of WE projects, including job creation, economic development, and local procurement opportunities, can boost social acceptance and support within host communities, primarily through community-focused initiatives [133].

3.5. Ocean Thermal Energy Conversion

3.5.1. Potential applications

OTEC, or ocean thermal energy, is a promising renewable energy source that uses the temperature difference between warm surfaces and cold deep waters to generate electricity, offering consistent power generation in tropical and subtropical regions [134]. OTEC systems aid in desalination processes, addressing coastal freshwater scarcity by evaporating and condensing seawater, providing a sustainable and drought-resistant solution [135]. OTEC can facilitate the cultivation of aquaculture. Cold, nutrient-rich water brought to the surface during OTEC operation can support the growth of marine organisms such as seaweed, shellfish, and fish. This can lead to the development of offshore aquaculture farms, enhancing food security and creating economic opportunities in coastal areas [136]. OTEC can support air conditioning and refrigeration systems by using cold water from deep ocean layers, reducing energy consumption and greenhouse gas emissions [137]. OTEC facilities can promote sustainable tourism and recreation by serving as artificial reefs, creating marine biodiversity, and integrating into eco-friendly resorts and attractions [138]. OTEC systems can produce hydrogen through seawater electrolysis, generating electricity for electrolyzers. This process can serve as a clean fuel for transportation, industrial applications, and energy storage, reducing fossil fuel reliance [139].

3.5.2. Advantages & disadvantages

OTEC is a promising renewable energy source due to its abundance and consistency, as it harnesses the stable temperature gradient between warm surface and cold deep water [140]. OTEC plants provide a reliable, stable baseload power supply without dependence on weather or daylight hours. They have a long operational lifespan with minimal maintenance requirements, making them attractive for electricity generation [141]. OTEC operation provides cold, nutrient-rich water for aquaculture and mariculture industries, supporting sustainable seafood production and diversifying economies in coastal communities [142]. The technology offers the potential for thermal energy storage, utilizing excess energy during low demand to heat a storage medium, thereby enhancing grid stability and flexibility [143]. OTEC faces high initial capital costs and complex engineering for deep-water operation, making it less economically competitive than conventional fossil fuel-based power generation [144]. These systems may have environmental impacts, particularly during the intake and discharge of seawater. Introducing large volumes of cold water to the surface could change local marine ecosystems and affect marine life distribution. Moreover, OTEC operations may disrupt ocean currents and nutrient cycles, potentially leading to unintended ecological consequences [145]. OTEC's efficiency is hindered by the temperature gradient between surface and deep ocean waters, and their geographical applicability is limited by suitable coastal locations with access to deep water [146].

3.5.3. Environmental impact

OTEC systems, a renewable energy source, have potential environmental impacts, including disruption of marine ecosystems due to the intake and discharge of seawater. This process can change local water temperatures, creating thermal plumes and affecting marine life distribution and behavior [147]. OTEC infrastructure construction may cause habitat disturbance, noise pollution, and physical barriers, potentially impacting marine species' migratory patterns, feeding behaviors, and reproductive cycles [148]. OTEC operations may indirectly affect the environment through energy extraction and resource utilization, contributing to carbon emissions, resource depletion, and pollution from extraction processes [149]. OTEC operations may disrupt oceanographic processes and nutrient cycles, potentially affecting marine ecosystems' primary productivity, species composition, and food web dynamics [150]. The efficiency of OTEC depends on the temperature gradient between surface and deep ocean waters, which may be insufficient in some regions, necessitating alternative energy sources or infrastructure investments [151].

3.5.4. Economic performance

OTEC systems generate electricity using temperature gradients and have economic viability based on resource availability and technological advancements. They are more favourable in tropical regions with consistent temperature differentials but uncertain in less pronounced areas [152]. Operational expenses like maintenance, monitoring, and staffing contribute to OTEC energy production costs, which are lower than those of conventional fossil fuel plants but still require regular maintenance for optimal performance [153]. The economic performance of OTEC systems is influenced by revenue generation, including electricity sales, ancillary services, and market factors like energy prices, government incentives, and regulatory frameworks [154]. OTEC's economic competitiveness is influenced by its renewable nature and baseload power generation potential. Still, due to their costs and environmental impacts, they must compete with established technologies like solar, wind, and fossil fuels [155].

3.5.5. Social acceptance

OTEC, a clean energy source, faces challenges in community acceptance due to perceived environmental impact. Concerns about disruptions to marine ecosystems, oceanographic processes, and habitat disturbances can influence public perception. Addressing these concerns through transparent communication and mitigation measures is crucial for gaining social acceptance [156]. The development of OTEC initiatives, despite potential job creation, economic growth, and energy security benefits, can be influenced by concerns about affordability, cost-effectiveness, and distribution of economic benefits [157]. The cultural context of OTEC deployment affects its acceptance among indigenous communities and traditional stakeholders, raising concerns about cultural heritage preservation, land rights, and community sovereignty. Respecting indigenous knowledge systems and incorporating local perspectives is crucial [158]. Public participation and stakeholder engagement are critical for building social acceptance of OTEC projects and enhancing transparency, accountability, and trust through ongoing dialogue and community feedback [159]. Education and awareness raising are crucial for shaping public attitudes towards OTEC, empowering communities to make informed decisions, and promoting social acceptance of this promising renewable energy technology.

3.6. Salinity Gradient Power

3.6.1. Potential applications

SGP, or blue energy, uses the difference in osmotic pressure between freshwater and saltwater to generate electricity, offering a sustainable alternative to fossil fuels in renewable energy generation [160]. SGP is utilized in desalination processes to address water scarcity, reduce energy costs, and enhance sustainability, making it more accessible and environmentally friendly [161]. SGP has potential for energy storage systems, storing renewable energy for grid stability. It can be integrated into pressure retarded osmosis systems, separating freshwater and saltwater for storage [162]. SGP can be integrated into wastewater treatment processes, reducing reliance on conventional energy sources and generating additional electricity, making the process more sustainable and energy efficient [163]. Despite challenges like technological feasibility and environmental impact assessments, SGP, a renewable energy solution, offers diverse applications in energy generation, desalination, storage, agriculture, aquaculture, and wastewater treatment.

3.6.2. Advantages & disadvantages

SGP, a renewable energy source, is a reliable and predictable source of electricity due to the continuous mixing of freshwater and seawater, unlike finite fossil fuel resources [159]. SGP plants can integrate with existing infrastructure in coastal areas, reducing costs and environmental impacts and providing a stable baseline for other renewable energy sources [164]. SGP can address water scarcity and quality issues in desalination by using the difference in osmotic pressure between freshwater and seawater, providing sustainable, energy-efficient, and environmentally friendly alternatives [165]. The extraction of energy from salinity gradients can alter water flow patterns and impact aquatic ecosystems, necessitating careful evaluation and mitigation measures to minimize adverse effects [166]. SGP, a renewable energy source, offers benefits like infrastructure integration and sustainable desalination but requires further research, development, and policy support to realize its full potential.

3.6.3. Environmental impact

SGP plants, which extract energy from freshwater and saltwater mixing, can disrupt aquatic ecosystems by altering water flow patterns, affecting sediment transport, nutrient cycling, and ecosystem processes [167]. Intake structures in power generation processes can trap and harm marine organisms, requiring careful design and operation to minimize harm [168]. Infrastructure installation for SGP systems may lead to habitat loss, land use change, and carbon emissions, disrupting ecosystems and contributing to greenhouse gas emissions. SGP, a renewable energy source with minimal greenhouse gas emissions, faces environmental effects like water flow changes and marine organism entrainment, requiring sustainable practices and ongoing research.

3.6.4. Economic performance

The commercial viability of SGP is a complex issue influenced by factors like capital costs, operational expenses, energy efficiency, and market dynamics. The high capital costs of constructing and deploying SGP plants and site-specific considerations pose significant challenges [169]. Operational expenses, including maintenance and environmental impact management, significantly impact SGP's economic performance. Energy generation efficiency, often lower than other renewables, is crucial. Improving osmotic power generation efficiency, including membrane technology and turbine design, is essential [170]. Advancements in membrane technology, turbine design, and system optimization can reduce capital costs, improve energy efficiency, and enhance economic competitiveness while integrating SGP with other renewable energy sources, providing additional revenue streams [171, 172].

3.6.5. Social acceptance

Public awareness, perceptions, and stakeholder engagement influence social acceptance of SGP. Raising public awareness about SGP's potential benefits and impacts, including its environmental benefits compared to traditional fossil fuels, is crucial for building social acceptance. Public outreach efforts, community meetings, educational campaigns, and media coverage can engage residents and stakeholders in discussions about SGP [173]. Concerns about potential negative impacts of SGP plants, such as changes in water flow patterns or disruption of ecosystems, can influence decision-making processes, thereby building trust and social acceptance [168], [174]. Developers can enhance the social acceptance and sustainable development of SGP by addressing community concerns, engaging stakeholders, and incorporating local perspectives into project planning and design.

4. Discussion: Opportunities and Challenges for the Energy Market

4.1. Market Potential

The market potential of marine energy technologies is substantiated by their ability to offer a reliable and sustainable source of clean electricity. As revealed in the findings, OSW, TE, WE, OTEC, and SGP collectively contribute to a diverse portfolio of renewable energy sources. With their vast potential applications and consistent energy generation from solid sea winds, OSW projects are positioned to meet the rising global electricity demand. TE, derived from ocean tides, presents an opportunity for consistent and predictable electricity generation. Despite facing challenges such as high costs and potential environmental impacts, TE contributes to grid stability, reducing dependence on fossil fuels. WE, harnessing the power of ocean waves, stands out for its clean and renewable nature, mitigating air and water pollution. Using the temperature difference between warm surfaces and cold deep waters, OTEC is a promising solution, especially in tropical and subtropical regions. Furthermore, SGP, or blue energy, provides a sustainable alternative by utilizing osmotic pressure differences between freshwater and saltwater for electricity generation. The study finds that SGP has diverse applications, including desalination, energy storage, and wastewater treatment, underscoring its potential to address multiple challenges through a single technology. Marine energy technologies' market potential is rooted in their technical capabilities and alignment with the growing consumer demand for sustainable, eco-friendly energy solutions. The findings emphasize that these technologies can be seamlessly integrated into the broader renewable energy landscape, catering to the preferences of environmentally conscious consumers. The ability of marine energy to reduce reliance on traditional fossil fuels positions it as a critical player in the ongoing energy transition. The market potential of marine energy technologies is robust, driven by their technical capabilities, sustainability, and alignment with consumer demands for clean energy. The diverse range of applications, from OSW to SGP, collectively positions marine energy as an essential force in shaping the future of the global energy market.

4.2. Consumer Perception and Adoption

The study's findings shed light on how consumers perceive and adopt marine energy technologies, offering insights into their awareness, attitudes, and preferences. Examining OSW, TE, WE, OTEC, and SGP, it becomes evident that consumer perception plays a vital role in successfully integrating these technologies into the mainstream energy landscape. With their visibility on coastlines and reliance on solid sea winds, OSW projects have the potential to shape positive perceptions among consumers who associate them with clean and renewable energy. The study underscores that consumer adoption of OSW is influenced by environmental benefits, understanding of the technology, and confidence in its reliability. Effective communication strategies that highlight the positive environmental impact and contribute to reducing carbon footprints are essential for garnering consumer support. While offering consistent and predictable electricity generation, TE may face challenges in consumer adoption due to concerns about environmental impacts and high upfront costs. The study indicates that consumers will likely embrace TE when adequately informed about its benefits, including grid stability and reduced dependence on fossil fuels. Building awareness and addressing consumer concerns through transparent communication are critical factors for enhancing the adoption of TE technologies. The findings reveal that WE is perceived positively for its clean and renewable nature. However, challenges such as high upfront costs and potential environmental impacts may influence consumer attitudes. Strategies emphasizing long-term benefits, including reduced air and water pollution, are crucial for shaping positive perceptions and driving consumer adoption of WE. OTEC and SGP, being relatively newer concepts, require targeted efforts in educating consumers about their potential applications and benefits. The study suggests that consumer perception of OTEC can be positively influenced by showcasing its role in desalination, aquaculture support, and clean fuel production. Similarly, for SGP, conveying the diverse applications beyond electricity generation, such as desalination and wastewater treatment, contributes to developing a positive perception among consumers. Consumer perception and adoption of marine energy technologies are intricately linked to effective communication, awareness-building, and addressing potential concerns. The study underscores the need for tailored marketing strategies that highlight the environmental benefits and economic advantages of these technologies and the role of these technologies in contributing to a sustainable energy future.

4.3. Marketing and Communication Strategies

The study provides valuable insights into the marketing and communication strategies essential for promoting the adoption of marine energy technologies. Effective communication is a linchpin for enhancing public awareness, understanding, and acceptance of OSW, TE, WE, OTEC, and SGP. OSW Marketing strategies should emphasize its potential applications in renewable energy generation, supporting offshore installations, and contributing to green energy ecosystems. The study highlights that clear communication about the benefits, including large-scale electricity generation, job creation, and infrastructure development, is essential. Engaging with local communities through informational campaigns can address concerns and build support. Communication strategies for TE should highlight its reliability and contribution to grid stability. The study suggests that marketing efforts should educate the public about the advantages of tidal barrages and turbines, dispel myths about environmental impacts, and showcase successful projects. Involving local communities in decision-making processes and addressing concerns transparently contribute to effective communication. Marketing and communication strategies for WE should focus on its potential applications, environmental benefits, and economic advantages. The study indicates that highlighting wave energy's role in electricity generation, job creation, and coastal protection is crucial for gaining public support. Utilizing educational campaigns, engaging with local stakeholders, and emphasizing long-term sustainability can contribute to successful communication. As they are relatively newer technologies, marketing strategies for OTEC and SGP should prioritize educational campaigns. The study suggests that conveying the diverse potential applications, including desalination, aquaculture support, and clean fuel production, is essential. Marketing efforts should underscore these technologies' sustainability, efficiency, and economic viability. Collaboration with research institutions and government agencies can strengthen communication channels. The study underscores that effective marketing and communication strategies for marine energy technologies should be tailored to address specific consumer concerns, highlight environmental and economic benefits, and build a sense of community involvement. Collaborative efforts between businesses, policymakers, and local communities are important for successful communication and the widespread adoption of marine energy solutions.

4.4. Economic Viability and Investment

The study searches into the economic landscape of marine energy projects, offering valuable insights into their viability, investment opportunities, and potential business models. Understanding the economic dimensions is crucial for stakeholders, investors, and policymakers involved in shaping the future of marine energy. Investing in OSW projects requires a comprehensive evaluation of capital costs, operational expenses, and revenue generation. The study emphasizes that despite high upfront costs, OSW farms offer several economic advantages, including higher capacity and job creation. To enhance economic viability, strategic considerations include leveraging economies of scale, improving infrastructure development, and exploring financing mechanisms. TE projects face economic challenges, including high capital costs and complex engineering requirements. The study underscores the importance of evaluating operational expenses, energy generation efficiency, and market dynamics. It suggests that economic viability can be improved by investing in technological advancements, optimizing maintenance strategies, and exploring partnerships to attract investment.

The economic performance of WE projects depends on factors such as initial investment, operational expenses, and revenue generation. The study indicates that technological advancements and economies of scale are expected to enhance cost-effectiveness despite challenges. Strategic considerations include developing innovation, supporting research and development initiatives, and exploring collaborative funding models to attract investors. Investment in OTEC and SGP projects necessitates a thorough understanding of capital costs, operational expenses, and revenue streams. The study highlights that economic competitiveness is influenced by renewable nature and baseload power generation potential. Focusing on research and development, improving energy production efficiency, and exploring synergies with other renewable sources are essential to attract investment. The study underscores that government policies and incentives play an important role in shaping the economic landscape of marine energy. Incentivizing research and development, providing financial support, and creating a conducive regulatory environment can build economic growth in the marine energy sector. The economic viability of marine energy projects requires a multifaceted approach, including strategic investments, technological innovation, and supportive policies. Stakeholders and investors are encouraged to consider the long-term benefits, such as reduced dependence on fossil fuels, job creation, and sustainable economic development, to realize the full potential of marine energy.

4.5. Stakeholder Engagement

Stakeholder engagement emerges as a critical factor influencing the success and growth of marine energy projects, as highlighted in the study. Effective collaboration and communication among stakeholders, including businesses, policymakers, and local communities, are essential for overcoming challenges and promoting the sustainable development of marine energy.

The study underscores the importance of stakeholder engagement in OSW projects, emphasizing the need for transparent communication and collaboration. The construction of offshore infrastructure can face environmental impact and local acceptance challenges. Stakeholder engagement strategies involve actively involving local communities, addressing concerns through ongoing dialogue, and incorporating feedback into project planning. This collaborative approach enhances trust and legitimacy, developing a positive environment for the OSW industry.

For TE projects, engaging stakeholders is crucial for addressing concerns related to environmental impact and economic benefits. The study suggests that effective communication and involvement in local communities can positively influence the development of TE technologies. By acknowledging and incorporating local perspectives, stakeholders can ensure that TE projects align with community needs, developing social acceptance.

Stakeholder engagement is vital in building trust and gaining social acceptance in the WE sector. The study highlights the importance of addressing concerns about WE devices, environmental impact, and potential disruptions. Engaging with local communities through community-focused initiatives, transparent communication, and proactive involvement in addressing challenges contributes to positive stakeholder engagement. Engaging stakeholders in OTEC and SGP projects is essential for navigating challenges and promoting acceptance. The study emphasizes the need for ongoing dialogue, community feedback, and transparent communication to address concerns about affordability, cost-effectiveness, and distribution of economic benefits. Incorporating local perspectives, respecting cultural heritage, and ensuring community participation contribute to effective stakeholder engagement. The study concludes that stakeholder engagement is not just a prerequisite for addressing challenges but also a catalyst for innovation and sustainable development in the marine energy sector. Governments, businesses, and policymakers are encouraged to prioritize stakeholder involvement, considering local context, cultural sensitivities, and collaborative decision-making processes. Stakeholder engagement can pave the way for successfully integrating marine energy projects into communities, promoting a cleaner and more sustainable energy future by developing a sense of ownership and inclusivity.

4.6. Comparative Analysis of MRE Technologies

Table 1 presents a comprehensive analysis of six separate types of marine renewable energies, each effectively utilizing the extensive capabilities of marine habitats in distinctive manners [48,86,91,134,138,165]. The sources encompassed in this study are FSP, offshore windmills, TE, harnessing ocean waves, OTEC, and SGP. Each of these sources possesses distinct uses, advantages, and limitations.

FSPs are a novel methodology that leverages the hydrological characteristics of lakes, reservoirs, and tranquil coastal regions. Their primary benefit stems from their ability to optimize space utilization and the inherent cooling properties of water, which can significantly improve performance. Nevertheless, it is crucial to approach difficulties such as reliance on meteorological conditions and the potential biological consequences on aquatic environments with caution. Offshore windmills are large and powerful structures located in deep waters, far away from coastlines, that consistently generate enormous amounts of energy. The significant negatives of these entities include their visual prominence and the maintenance issues that arise from the aquatic environment. Furthermore, implementing and functioning these systems can result in minor environmental consequences, such as the emission of noise and potential ramifications for marine organisms. TE harnesses the foreseeable and potent tidal patterns in coastal regions, demonstrating exceptional efficiency and energy forecasting. However, the environmental issues associated with its capacity to modify tidal patterns and marine habitats and substantial upfront infrastructure expenses pose considerable obstacles. Utilizing ocean waves for power exploits the plentiful and sustainable wave energy resource in coastal regions with constant wave patterns. The technology continues to encounter obstacles in terms of its efficiency and environmental consequences, compounded by the added intricacy of being in its early phases of development, which now impacts its economic feasibility. Ocean Thermal Energy Conversion (OTEC), well-suited for tropical locations, utilizes the temperature difference between the warmer surface water and the cooler deep water to produce energy. Notwithstanding its considerable potential and consistent accessibility, OTEC presents technological complexities and necessitates substantial initial capital outlay, albeit it presents enduring economic advantages in certain contexts. The developing technology known as SGP aims to use the energy potential present at the interface between freshwater and saltwater, namely in estuaries. It is notable for its sustainable methodology, which has a minimum ecological footprint. Nevertheless, as a nascent technology, it encounters obstacles to its originality and the limited availability of appropriate sites. The economic performance of these technologies exhibits significant variation, contingent upon factors such as geographical location, scale, technological advancement, and initial investment expenses. The level of social acceptance varies, taking into account factors such as the visual and noise effects of offshore windmills and the creative attractiveness of SGP. This study undertakes a comparative analysis of marine renewable energies, focusing on each technology's varied potential and constraints. In the context of global efforts toward sustainable energy solutions, it is imperative for stakeholders, policymakers, and researchers to possess a comprehensive awareness of these intricacies. This knowledge is essential for making well-informed decisions on the future of energy production and the responsible management of the environment.

Table 1. Comparative Analysis of MRE Technologies

Marine Renewable Energy (MRE)	Potential Applications	Advantages & Disadvantages	Environmental Impact	Economic Performance	Social Acceptance
Floating Solar Panels (FSPs)	Lakes, reservoirs, and calm sea areas	***Adv*** Space-efficient, water-cooling ***Disadv*** Weather-dependent, ecological impact	Low; potential for water ecosystem disruption	Variable; dependent on location and technology maturity	Generally high; if low visual impact
Offshore Wind (OSW)	Deep waters away from the coastline	***Adv*** High energy output, consistent ***Disadv*** Visual impact, maintenance challenges	Moderate; noise and possible effects on marine life	Generally good; benefits from economies of scale	Mixed; concerns over visual impact and noise
Tidal Energy (TE)	Coastal areas with strong tidal movements	***Adv*** Predictable energy, high efficiency ***Disadv*** Environmental concerns, high initial cost	Moderate to High; can affect tidal flow and marine habitats	High initial investment but low operational costs	Depends on local impact; can be high with proper engagement
Wave Energy (WE)	Coastal areas with consistent wave patterns	***Adv*** Renewable, abundant source ***Disadv*** Technology challenges, environmental impact	Moderate; may alter marine ecosystems and shorelines	Currently high due to nascent technology	Emerging acceptance; dependent on visibility and noise
Ocean Thermal Energy Conversion (OTEC)	Tropical regions with significant ocean temperature gradients	***Adv*** Huge potential, constant availability ***Disadv*** Technically challenging, high-cost	Low to Moderate; depends on scale and location	High initial costs; economic in the long-term for suitable locations	Varies; higher in regions with energy deficits
Salinity Gradient Power (SGP)	Areas where freshwater meets saltwater (estuaries)	***Adv*** Sustainable, low environmental impact ***Disadv*** Emerging technology, limited locations	Low; minimal interference with marine ecosystems	Early stage; potential for high long-term return	Generally positive; seen as innovative and less intrusive

*Note: This table and subsection were constructed based on the author's ideas from the literature review.

5. Conclusion

The global energy transition towards cleaner and more sustainable alternatives represents a pivotal response to pressing environmental challenges, aiming to mitigate greenhouse gas emissions, combat climate change, and enhance energy security. Environmental imperatives, technological advancements, policy initiatives, and economic considerations drive this transition. Within this context, marine energy technologies emerge as promising contributors to diversifying the renewable energy portfolio and reducing reliance on traditional fossil fuels. This comprehensive study has provided insights into the multifaceted realm of marine energy technologies, encompassing offshore wind (OSW), tidal energy (TE), wave energy (WE), ocean thermal energy conversion (OTEC), and salinity gradient power (SGP), shedding light on their technical, environmental, and socio-economic dimensions.

The findings underscore the vast potential of marine energy in addressing global energy challenges. Despite inherent challenges such as high upfront costs, environmental impact concerns, and the intermittency of some sources, ongoing technological innovations and concerted global efforts to combat climate change are driving increased interest and investment in marine energy projects worldwide. Exploring the market potential of marine energy technologies reveals their significant role in diversifying the renewable energy landscape and meeting growing electricity demand. Specifically, OSW, TE, WE, OTEC, and SGP offer unique advantages and applications, from consistent energy generation to sustainable desalination and wastewater treatment solutions.

Consumer perception and adoption patterns play a crucial role in shaping the future trajectory of marine energy technologies. As consumers increasingly prioritize sustainability, there is a growing awareness and positive attitude towards marine energy. Effective marketing and communication strategies highlighting marine energy technologies' environmental benefits, economic advantages, and reliability are essential for fostering greater acceptance and adoption in the energy market.

The economic viability of marine energy projects is contingent upon various factors, including investment opportunities, returns, and business models. Despite initial challenges, these projects offer several economic advantages, including higher capacity factors, job creation, and infrastructure investment. Government policies and incentives play a pivotal role in shaping the business landscape for marine energy, providing further impetus for investment and innovation.

Stakeholder engagement is critical to success and growth in the marine energy sector. Collaboration among businesses, policymakers, and local communities is indispensable for addressing challenges and promoting sustainable development. Transparent communication, ongoing dialogue, and incorporating local perspectives are essential for enhancing stakeholder engagement and building trust.

Embracing the vast potential of ocean-based energy sources is imperative for navigating towards a cleaner, more resilient energy future. Continued research, investment, and collaboration among governments, industries, and research institutions are essential to unlocking the full potential of marine energy and ensuring a sustainable and inclusive energy transition. As marine energy technologies evolve, the insights gleaned from this study provide a roadmap for navigating challenges and realizing the promise of a cleaner, greener energy landscape.

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