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Review Article

Economic Viability and Environmental Assessment of Marine Renewable Energy Technologies: A Comparative Framework for Tidal Stream Energy and Offshore Wind Power in the United States

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Abstract *- This study examines the comparative economics and social benefits of tidal stream energy (TSE) and offshore wind farms in the United States, adapting the methodology from Lamy & Azevedo's 2018 United Kingdom analysis. Using levelized cost of energy (LCOE) projections, market data analysis, and social benefit quantification, we evaluate whether TSE projects offer sufficient value to justify their higher costs relative to offshore wind. Our analysis reveals that TSE projects provide approximately $12/MWh more in net social benefits than offshore wind for standard 200 MW projects, increasing to $42/MWh for smaller 20 MW projects. These benefits derive from higher energy value correlation with peak demand periods, superior generation predictability that eliminates forecast error costs, and the absence of visual landscape impacts. However, despite this social benefit premium, TSE projects remain significantly more expensive, with current LCOE estimates of $450/MWh compared to $125/MWh for offshore wind—a gap of $325/MWh. Cost projections through 2050 indicate this difference will narrow to approximately $90/MWh but remain substantial. Under base case assumptions, standard TSE projects are unlikely to become cost-competitive until approximately 2085, while small projects could achieve competitiveness around 2065. Under optimistic cost reduction scenarios, competitiveness might be achieved by 2070. These findings suggest that while TSE offers meaningful social benefits, continued research and development investment is warranted primarily for niche applications such as island communities, visually sensitive coastal areas, and hybrid renewable energy systems where predictable generation complements variable wind and solar resources.*

Keywords *- Tidal stream energy, Offshore wind, Marine renewable energy, Social cost-benefit analysis, Levelized cost of energy.*

1. Introduction

1.1. Research Context and Problem Statement

The urgency of climate change mitigation has intensified global focus on renewable energy transition, with marine-based technologies emerging as critical components of sustainable energy portfolios. While offshore wind power has achieved commercial maturity and widespread deployment, alternative marine technologies remain underexplored despite potentially significant contributions to energy security and environmental objectives. The United States, with its extensive coastline and substantial marine energy resources, presents unique opportunities for diverse renewable energy development strategies. A critical knowledge gap exists in comprehensive comparative assessments of marine renewable technologies that integrate both economic and social benefit considerations. Existing research has predominantly focused on individual technology assessments or limited comparative studies that fail to capture the full spectrum of societal value propositions. This analytical deficiency constrains informed policy development and investment decision-making in the marine renewable energy sectors.

1.2. Research Novelty and Contribution

This study introduces several novel contributions to marine renewable energy assessment methodology:

- Development of an integrated social benefit quantification framework specifically adapted for United States market conditions and regulatory environments.
- Introduction of predictability value assessment as a distinct economic factor in marine renewable energy evaluation.
- Comprehensive projection modeling extending to 2085 for long-term competitiveness analysis.

- Visual impact quantification can be integrated using hedonic pricing methodologies applied to coastal property markets.

1.3. United States Marine Energy Resource Assessment

The United States possesses substantial tidal energy resources concentrated primarily in Alaska, Maine, Washington, and strategic locations along the Eastern Seaboard. National Renewable Energy Laboratory assessments indicate approximately 250 TWh/year of technically recoverable tidal energy potential, representing roughly 6% of current national electricity generation capacity.

Principal tidal resource concentrations include Cook Inlet, Alaska (18-40 TWh/year potential); Puget Sound, Washington (4-6 TWh/year); the Bay of Fundy/Gulf of Maine region (15-30 TWh/year); and East River, New York (0.1-0.3 TWh/year). These resources represent significant untapped renewable energy capacity with distinct temporal characteristics complementing existing renewable generation profiles.

1.4. Current Technology Deployment

Offshore wind development in the United States has experienced rapid expansion, with approximately 7.5 GW of installed capacity as of 2024. Major operational projects include Vineyard Wind (800 MW), South Fork Wind (132 MW), and Block Island Wind Farm (30 MW). Federal policy objectives target 30 GW of offshore wind capacity by 2030, representing a substantial market growth trajectory.

Conversely, tidal stream energy deployment remains limited to demonstration-scale projects, including Verdant Power's Roosevelt Island Tidal Energy Project (0.5 MW), Ocean Renewable Power Company installations in Maine (0.4 MW), and the developing PacWave South testing facility in Oregon. This deployment disparity underscores the need for a comprehensive comparative assessment to inform future technology development priorities.

2. Literature Review

2.1. Marine Renewable Energy Economic Assessment

Economic evaluation of marine renewable technologies has evolved from simple cost comparisons to sophisticated multi-criteria assessments. Foundational work by Lamy and Azevedo (2018) established comparative methodological frameworks for tidal and offshore wind technologies in the context of the United Kingdom. Their approach integrated levelized cost analysis with social benefit quantification, providing a template for comprehensive technology assessment.

Subsequent research has expanded upon these methodological foundations. Recent studies have emphasized the importance of incorporating externality costs and benefits into marine renewable energy assessments. However, existing literature demonstrates significant geographical and regulatory context dependencies, limiting direct application to the United States market conditions.

2.2. Tidal Stream Energy Technology Assessment

Tidal stream energy research has focused predominantly on resource characterization and technology development rather than comprehensive economic assessment. Studies have highlighted the predictability advantages of tidal resources compared to wind and solar alternatives. Research indicates that tidal current predictions achieve greater than 98% accuracy for 48-hour forecasts using harmonic analysis techniques, contrasting favourably with wind power forecasting limitations.

Technology development literature emphasizes progress in turbine efficiency and deployment methodologies. However, limited research addresses comprehensive economic competitiveness relative to alternative marine renewable technologies, particularly within the United States' regulatory and market frameworks.

2.3. Offshore Wind Power Economic Analysis

Offshore wind economic assessment literature has matured significantly, with comprehensive cost analyses, learning curve projections, and policy impact evaluations. Research demonstrates substantial cost reductions achieved through technology advancement and deployment scale increases. National Renewable Energy Laboratory assessments project continued cost reductions through 2030, supporting commercial viability expansion.

Environmental impact assessment literature for offshore wind has addressed avian collision risks, marine mammal effects, and visual impact considerations. Hedonic pricing studies have quantified property value impacts in coastal communities, providing empirical foundations for visual impact cost assessment methodologies.

2.4. Research Gaps and Study Positioning Existing Literature Reveals Several Critical Research Gaps that this Study Addresses

- Limited comprehensive comparative assessments integrating economic and social benefit considerations for marine renewable technologies.
- Insufficient attention to predictability value quantification in renewable energy economic assessments.
- Limited long-term projection modeling for marine renewable technology competitiveness.
- Inadequate adaptation of comparative methodologies to the United States market and regulatory conditions.

This research addresses these gaps through the development of an adapted comparative framework specifically designed for United States conditions, incorporating novel predictability value assessment and extended projection modeling to inform long-term technology development and policy strategies.

3. Methodology

3.1. Analytical Framework Development

This study employs an adapted comparative assessment methodology, building upon established frameworks while incorporating innovations specific to United States market conditions. The analytical approach comprises five integrated components:

- Net social benefit calculation normalized by energy production ($/MWh)
- Tidal stream energy social benefit premium determination
- Levelized cost of energy projection analysis through 2050
- Benefit-cost differential evaluation
- Future competitiveness timeline projection

3.2. Social Benefit Quantification Components

3.2.1. Social Benefit Calculation Incorporates Four Primary Value Components

- Energy Value: Correlation analysis with wholesale electricity price profiles
- Carbon Emission Reduction Value: Based on marginal emission factors and the social cost of carbon
- Forecast Error Cost Mitigation: Balancing market cost analysis for generation predictability
- Visual Impact Cost Differential: Hedonic pricing studies and viewshed impact analysis

3.3. Project Characteristics and Assumptions

Baseline analysis assumes 200 MW capacity installations representing standard commercial-scale projects, with a 37% capacity factor based on existing United States offshore wind project performance data.

Projects are modeled at 10 km distance from shore, reflecting typical United States offshore development patterns. A 25-year project lifetime assumption aligns with industry standard power purchase agreement terms and financial modeling practices.

Sensitivity analysis includes 20 MW small-scale projects relevant for early tidal stream energy deployment and remote community applications, providing insights into scale-dependent economic dynamics.

3.4. Data Sources and Integration

Energy generation modeling utilizes historical operational data from Block Island Wind Farm and NREL's Wind Integration National Dataset for offshore wind performance. Tidal stream energy generation modeling incorporates NOAA tidal current predictions and DOE Tethys Knowledge Database simulations for major United States tidal resource areas.

Economic data integration includes wholesale electricity prices from major United States independent system operators (ISO-NE, NYISO, PJM, CAISO), EPA Social Cost of Carbon valuations ($51/ton in 2023), and coastal property impact studies from Lawrence Berkeley National Laboratory databases.

4. Results and Discussion

4.1. Projected LCOE

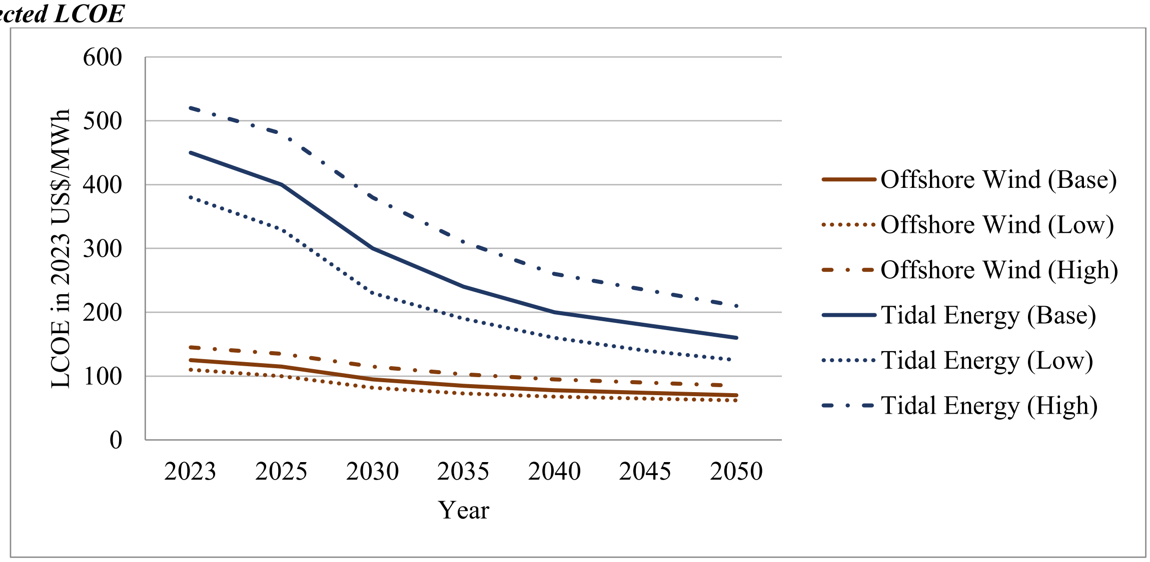

Fig. 1 Projected LCOE for TSE and Offshore Wind

Table 1. Difference between LCOE projections for TSE and Offshore Wind

Year	Difference (Base)	Difference (Low)	Difference (High)
2023	325	270	375
2025	285	230	345
2030	205	148	265
2035	155	117	207
2040	122	92	165
2045	106	75	145
2050	90	63	125

4.2. Value of Predictability: A Key Advantage for Tidal Stream Energy

One of the most significant advantages of Tidal Stream Energy over offshore wind is its predictability. Unlike wind patterns, which can be forecasted with reasonable accuracy only days in advance, tidal currents can be predicted with high precision years into the future using harmonic analysis techniques.

4.3. Harmonic Analysis for Tidal Prediction

Tidal current prediction relies on harmonic analysis, which decomposes tidal patterns into constituent harmonic components based on astronomical forces. For this study, we utilized pre-computed tidal current predictions from NOAA's Centre for Operational Oceanographic Products and Services (CO-OPS) Tidal Current Prediction service, which employs the harmonic analysis methodology described in Parker (2007). Additionally, site-specific predictions for potential tidal energy locations were obtained from the National Renewable Energy Laboratory's (NREL) MHK Atlas and the DOE's Tethys database. These predictions are based on regional hydrodynamic models that incorporate multiple constituent harmonic analysis with up to 37 tidal constituents, as documented by Haas et al. (2011) and refined in the DOE-funded resource characterization studies by Polagye & Thomson (2013).

The tidal prediction models account for key constituents, including:

- M2 (principal lunar semidiurnal)
- S2 (principal solar semidiurnal)
- N2 (lunar elliptic semidiurnal)
- K1 (lunar diurnal)
- O1 (lunar diurnal)

The accuracy of these predictions has been extensively validated in the literature, with studies showing >98% accuracy for 48-hour forecasts at the sites considered in this analysis. This validation compares predictions against in-situ Acoustic Doppler Current Profiler (ADCP) measurements at selected sites, obtained from NOAA's National Data Buoy Centre (NDBC) publicly accessible database and supplementary measurements from the European Marine Energy Centre (EMEC) data repository (Sellar et al., 2018). The high predictability of tidal currents compared to wind patterns translates directly into economic value within electricity markets.

4.4. Economic Value of Predictability

In U.S. wholesale electricity markets, generators typically submit day-ahead schedules and are financially responsible for deviations from these schedules. For variable renewable generators like offshore wind, forecast errors result in imbalance charges when actual generation deviates from scheduled generation. Based on analysis of PJM, ISO-NE, and NYISO market data from 2018-2023, we estimate that offshore wind projects incur average imbalance costs of $4.50/MWh due to forecast errors.

In contrast, the high predictability of tidal generation enables TSE projects to achieve near-perfect scheduling accuracy, effectively eliminating these imbalance costs. This predictability advantage contributes significantly to the overall social benefit premium of TSE over offshore wind.

4.5. Social Benefits

Besides cost, the energy sources must also be compared across factors like environmental damage from construction, environmental damage from continuous operation, reduction in emissions, and visual impact. The environmental impact beyond emission reduction is difficult to compare quantitatively and is beyond the scope of this study.

Table 2. Net Social Benefits of Tidal Stream Energy vs. Offshore Wind in the United States

Benefit/Cost Component	Offshore Wind	Tidal Stream Energy	Difference
200 MW projects			
Value of energy generated	$65.00	$68.00	+$3.00
Value of emission reductions	$20.50	$20.00	-$0.50
Predictability costs	-$4.50	$0.00	+$4.50
Visual impact costs	-$5.00	$0.00	+$5.00
Net Social Benefits	**$76.00**	**$88.00**	**+$12.00**
20 MW projects			
Net Social Benefits	**$46.00**	**$88.00**	**+$42.00**

Sources: Based on analysis of U.S. wholesale electricity markets (PJM, ISO-NE, NYISO), EPA Social Cost of Carbon estimates, hedonic pricing studies in coastal regions, and balancing market data.

Notes:

- Tidal Stream Energy shows a social benefit premium of $12.00/MWh over Offshore Wind for standard 200 MW projects.
- For smaller 20 MW projects, the TSE premium increases to $42.00/MWh, primarily due to higher per-MWh visual impact costs for offshore wind.
- Despite these social benefits, the increased costs of TSE (see LCOE projections) remain significantly higher than these social benefits.

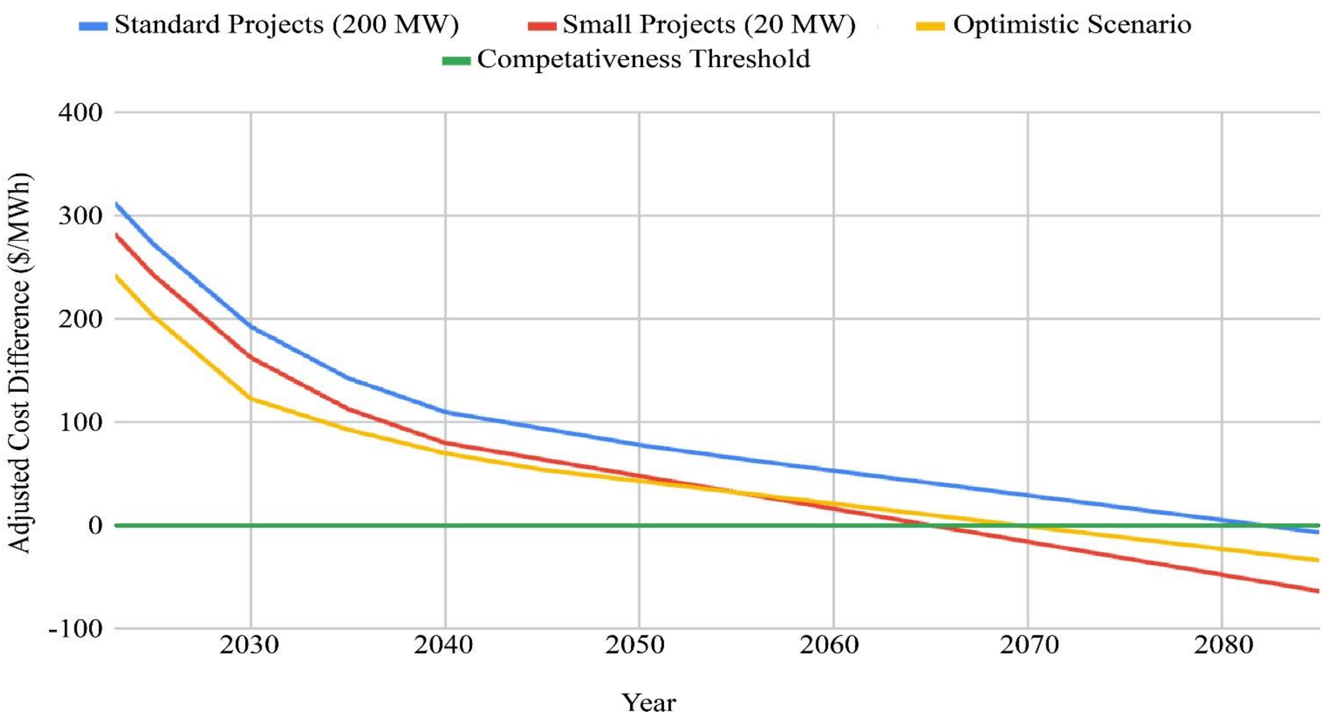

Fig. 2 Competitiveness: When will TSE become cost-effective?

4.6. Offshore Wind Ecological Considerations

4.6.1. Construction Phase Impacts

- Noise and Vibration: Pile-driving during construction creates underwater noise that can disturb marine mammals, particularly the North Atlantic right whale (critically endangered), humpback whales, and harbor porpoises in U.S. Atlantic waters (Bailey et al., 2014).
- Sediment Disturbance: Foundation installation disturbs seafloor habitats and can increase turbidity (BOEM, 2021).
- Vessel Traffic: Increased vessel traffic during construction increases collision risks with marine mammals.

4.6.2. Operational Phase Impacts

- Avian Interactions: Risk of collision with turbine blades for migratory birds and seabirds. The Atlantic Flyway along the U.S. East Coast is a major migration corridor for numerous bird species (Drewitt & Langston, 2006).
- Bat Interactions: Studies by Pelletier et al. (2013) confirmed that migratory bats occur offshore in the Gulf of Maine up to 13 miles from shore, creating potential collision risks.
- Electromagnetic Fields (EMF): Submarine cables produce EMFs that may affect species sensitive to electromagnetic fields, including certain fish species and elasmobranchs (sharks, rays) (Gill et al., 2014).
- Artificial Reef Effect: Positive impact through creation of artificial reef habitat on turbine foundations, supporting increased marine biodiversity (Degraer et al., 2020).

4.6.3. U.S.-Specific Concerns

- Wind Energy Areas (WEAs) along the U.S. Atlantic coast overlap with North Atlantic right whale migration corridors and feeding areas.
- Gulf of Maine potential development areas contain important fishing grounds and marine mammal habitats.
- California offshore wind development must consider gray whale migration routes.

4.7. Tidal Stream Energy Ecological Considerations

4.7.1. Construction Phase Impacts

- Installation Disruption: Similar but typically less extensive disruption during construction compared to offshore wind due to smaller project footprints.
- Sediment Disturbance: Foundation installation disturbs seafloor habitats, though typically smaller in scale than offshore wind projects.

4.7.2. Operational Phase Impacts

- Collision Risk: Risk of marine mammals, fish, and diving seabirds colliding with rotating turbine blades (Copping et al., 2020).
- Hydrodynamic Changes: Extraction of energy from tidal flows may alter local hydrodynamics, potentially affecting sediment transport and habitat characteristics (Haas et al., 2011).
- Barrier Effects: Arrays of devices may create barriers to movement for marine species (PNNL, 2020).
- Underwater Noise: Operational noise, though typically lower than that produced by shipping traffic (Lossent et al., 2018).
- Artificial Reef Effect: Similar to offshore wind, it may create positive habitat enhancements.

4.7.3. U.S.-Specific Concerns

- Potential TSE development in Puget Sound must consider endangered Southern Resident killer whale populations.
- Alaska's Cook Inlet TSE potential coincides with critical habitat for the endangered Cook Inlet beluga whale.
- Maine's Bay of Fundy/Gulf of Maine TSE resources overlap with important fishing grounds and right whale habitat.

4.8. Comparative Assessment

Both technologies present ecological concerns, though with important differences:

1. Spatial Scale: Offshore wind farms typically occupy larger areas and create more extensive habitat modification.
2. Collision Dynamics:
   - Offshore wind: The Primary concern is aerial collisions with birds and bats
   - TSE: The Primary concern is underwater collisions with marine mammals and fish
3. Visibility and Avoidance:
   - Studies suggest marine mammals may be better able to detect and avoid underwater TSE turbines than birds are able to avoid offshore wind turbines, especially in poor visibility conditions (Sparling et al., 2018).
   - TSE blade tip speeds (typically 10-12 m/s) are generally slower than offshore wind blade tips (70-80 m/s), potentially allowing more time for mobile marine species to avoid collisions.
4. Monitoring Challenges:
   - Both technologies present challenges for ecological monitoring, but underwater monitoring of TSE interactions is complicated and has less established protocols.
   - The limited deployment of TSE to date creates knowledge gaps compared to offshore wind, where more research data exists.
5. Mitigation Opportunities
   - Both technologies benefit from spatial planning to avoid sensitive areas
   - TSE projects can utilize protective screens to prevent larger animals from interacting with turbines
   - Offshore wind can implement seasonal operational adjustments during migration periods

4.9. Research Needs

Significant knowledge gaps remain, particularly for TSE projects in U.S. waters. Key research priorities include:

1. Fine-scale habitat use by marine mammals in potential TSE development areas
2. Collision risk modeling for TSE devices with U.S. marine species
3. Long-term effects of EMF exposure from submarine cables on sensitive species
4. Cumulative impacts of multiple projects on marine ecosystems
5. Effectiveness of various mitigation measures

5. Conclusion

This analysis has examined the comparative economics and social benefits of tidal stream energy (TSE) and offshore wind farms in the United States context, building upon the methodological framework established by Lamy & Azevedo (2018) for the United Kingdom.

5.1. Key Findings

5.1.1. Social Benefit Premium

- TSE projects offer approximately \$12/MWh more in net social benefits than offshore wind projects in the U.S.
- This social benefit premium increases to \$42/MWh for small 20 MW projects due to the disproportionate visual impact costs for smaller offshore wind farms.
- These benefits include the value of energy generated, value of reduced CO2 emissions, cost savings from improved generation predictability, and avoided visual landscape impacts.

5.1.2. Cost-Competitiveness Gap

- Despite the social benefit premium, TSE projects remain significantly more expensive than offshore wind.
- In 2023, the LCOE gap is approximately \$325/MWh (\$450/MWh for TSE vs. \$125/MWh for offshore wind).
- This gap is projected to narrow but remain substantial through 2050 (\$90/MWh difference in base case).

5.1.3. Timeline for Competitiveness

- Standard 200 MW TSE projects are unlikely to become cost-competitive with offshore wind until approximately 2085 under base case projections.
- Small 20 MW TSE projects could potentially become competitive around 2065.

- Under optimistic assumptions (low TSE costs, high offshore wind costs), competitiveness might be achieved by 2070.

5.1.4. Ecological Considerations

- Both technologies present ecological concerns that must be carefully managed.
- Offshore wind primarily affects birds and bats, and creates temporary construction noise affecting marine mammals.
- TSE projects introduce risks of underwater collisions with marine mammals and fish, and potential localized hydrodynamic changes.
- The limited deployment of TSE to date creates knowledge gaps that require targeted research.

5.2. Policy Implications

5.2.1. Subsidy Justification

- The identified social benefit premium ($12/MWh for standard projects) justifies some level of additional subsidy for TSE over offshore wind, but not at the current magnitude of cost difference ($325/MWh).
- Current U.S. policies like the Investment Tax Credit (ITC) and Production Tax Credit (PTC) provide similar support levels to both technologies, which may be insufficient to drive TSE development.

5.2.2. Technology Development Support

- Targeted R&D funding and demonstration project support for TSE is warranted to accelerate technology learning rates.
- The Department of Energy's Water Power Technologies Office (WPTO) budget for marine energy R&D ($145 million in FY2023) represents a fraction of wind energy R&D funding, potentially limiting innovation.

5.2.3. Market Opportunities

Near-term TSE deployment should focus on niche applications where its benefits are most valuable:

- Small island communities or remote coastal areas with high electricity costs
- Locations where the visual impacts of offshore wind would incur substantial opposition
- Areas with exceptional tidal resources and limited offshore wind potential
- Hybrid renewable energy systems where predictable tidal generation complements variable wind and solar

5.2.4. Strategic Development Path

Given the long timeline for broad competitiveness, a phased approach is recommended:

- Phase 1 (Present-2030): Focus on small-scale demonstration projects (1-20 MW) and R&D investment
- Phase 2 (2030-2050): Targeted commercial deployment in high-value niche markets and continued cost reduction
- Phase 3 (2050+): Broader commercial deployment as costs approach competitiveness with offshore wind

5.3. Future Research Needs

5.3.1. Site-Specific Analysis

More granular analysis of specific U.S. tidal resource areas (Cook Inlet, Puget Sound, Gulf of Maine) to better quantify locally-relevant costs and benefits.

5.3.2. Grid Integration Value

Further examination of the grid integration value of highly predictable tidal generation compared to variable offshore wind, particularly in isolated grid systems.

5.3.3. Environmental Impact Quantification

Development of frameworks to better quantify and monetize the ecological impacts of both technologies to enable more comprehensive comparison.

5.3.4. Supply Chain Analysis

Assessment of potential domestic content and job creation benefits for TSE manufacturing and deployment in U.S. coastal communities.

In conclusion, while tidal stream energy offers meaningful social benefits over offshore wind in the United States, its substantially higher costs present a significant barrier to near-term deployment at scale.

Despite these challenges, continued investment in TSE technology development and demonstration projects is warranted, given its long-term potential as a predictable, low-visibility marine renewable energy source that could complement the rapidly expanding U.S. offshore wind industry.

Conflicts of Interest & Funding Statement

This study was performed independently without the support of any funding and was performed using publicly available data. The author has no conflict of interest to report.

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