AN INTEGRATED HIGH-RESOLUTION ASSESSMENT OF WAVE AND TIDAL

ENERGY POTENTIAL ALONG THE NEW JERSEY COASTLINE

By

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ABSTRACT OF THE THESIS

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This study delivers a high-resolution, device-level assessment of tidal and wave energy potential along the New Jersey coastline to support the state's clean energy goals and address climate change and fossil fuel dependency. While offshore wind has been extensively studied, tidal and wave energy remain underexplored in New Jersey, particularly at fine scales. This report fills this gap by evaluating technical feasibility, environmental constraints, and regulatory frameworks for responsible marine renewable energy development.

The research utilized advanced numerical models to map resource availability. Tidal energy assessments employed Delft3D to simulate current velocities and power density from Delaware Bay to the New York Bight, with device-level analysis to match turbine technologies to local conditions. Wave energy assessments used the SWAN model to characterize spatial, temporal, and seasonal variability in nearshore and offshore wave climates. These analyses were integrated with GIS-based multi-criteria decision frameworks, incorporating ecological protections, navigation routes, and coastal infrastructure to identify conflict-free deployment sites.

The modeling results indicate that New Jersey's tidal energy resources are modest, with harnessable potential ranging from 24 to 88 MW, constrained by navigation channels, depth, and

sensitive habitats. Promising tidal sites include Hudson River, Barnegat Bay, Cape May, and two Delaware River locations one near Trenton and another between Philadelphia and Wilmington selected for accessibility and reduced waterway conflicts. Wave energy resources are moderate, with winter storms yielding the highest power (8–10 kW/m), and suitability analysis highlights four areas off Atlantic City as ideal for pilot wave energy converter projects. However, the model's limitations in simulating shoreline wave dynamics, coupled with significant wave attenuation due to New Jersey's wide continental shelf, preclude recommendations for onshore wave energy development.

The study concludes that tidal and wave energy can contribute to New Jersey's renewable energy portfolio if pursued strategically. Near-term opportunities include small-scale pilot projects at high-potential sites, with careful device selection to optimize performance. Long-term success requires streamlined permitting, ongoing environmental monitoring, and policy incentives to encourage investment in emerging technologies. By integrating high-resolution modeling with comprehensive environmental and regulatory analysis, this report provides a practical roadmap for advancing marine renewable energy within New Jersey's clean energy strategy, positioning the state as a mid-Atlantic leader. Further research on field measurements, long-term ecological impacts, and stakeholder engagement is recommended to refine deployment approaches.

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1 Introduction

1.1 Motivation

Growing concerns about climate change, energy security, and the environmental impact of fossil fuels have propelled the global community to seek cleaner, more sustainable energy sources (IPCC, 2021). Renewable energy technologies such as solar, wind, and bioenergy have seen significant advancements over the past few decades, yet marine renewable energy stands out for its potential to harness the vast and relatively untapped power of oceans (Kilcher et al., 2021). Within the realm of marine renewables, wave and tidal energy have attracted particular attention for their predictability and potentially high energy density (Falcão, 2010; Xia et al., 2010; Neill et al., 2021). Wave energy is contained in the motion and height of surface waves, while tidal energy can be harnessed from the regular rise and fall of sea levels and the associated flow driven primarily by gravitational forces of the moon and sun (Holthuijsen, 2007; Neill et al., 2021). Although these technologies are less mature compared to established renewables like wind or solar, their strategic importance is growing as nations seek to diversify and decarbonize their energy portfolios (Rusu & Onea, 2018; Astariz & Iglesias, 2015).

The New Jersey coastline presents a unique opportunity to explore these marine renewable energy options (Tang et al., 2014). Located in the Mid-Atlantic region, New Jersey has a moderate yet consistent ocean waves, consistent ocean waves, as well as tidal flows that are intermittent for energy generation (NOAA NDBC, 2022; NOAA CO-OPS, 2022). Proximity to large population centers further enhances the region's appeal, as electricity generated offshore can be delivered relatively easily to consumers. However, identifying the best locations for harnessing wave and tidal energy along this coastline requires a systematic assessment of physical resources, environmental constraints, and socioeconomic factors (Haas et al., 2011).

1.2 Problem Statement

Despite the promising outlook for ocean energy, there remain significant challenges in locating and developing optimal sites. The site selection process is highly multidisciplinary, involving oceanographic data (wave height, tide range, current velocity), environmental considerations (coastal habitats, aquatic vegetation, and marine protected areas), and economic and regulatory factors (Haas et al., 2011). In addition, to support decision making, a refined, device-level energy resources assessment is required, which has been rarely conducted in the literature. Although there has been substantial progress toward offshore wind in New Jersey, wave and tidal resources have been less systematically examined. While some initial assessments of the region's wave or tidal potential have been conducted (Tang et al., 2014), a comprehensive, site-specific analysis of both wave and tidal energy potential remains a gap in the literature.

This study aims to address the site selection challenge by examining the wave and tidal resources of the New Jersey coastline and identifying the most promising areas for development. A core aspect of this work involves balancing environmental considerations, such as marine habitats and protected areas, and human-use factors like shipping lanes and coastal communities, with the technical and economic feasibility of energy extraction (Azzellino et al., 2013; Flocard et al., 2016).

1.3 Research Questions and Objectives

The core of this study revolves around a pivotal research question: which areas along the New Jersey coastline stand out as the most suitable for harnessing wave and tidal energy in a manner that is both sustainable and economically viable? If there are suitable locations, how many resources can be harnessed? To address this inquiry, the study establishes several key objectives. The first objective focuses on resource characterization, which involves gathering and analyzing tidal and wave data sourced from publicly available repositories. This effort is complemented by employing numerical models, notably Delft3D and SWAN, to simulate the dynamics of tidal current and waves across the New Jersey coastline, providing a detailed understanding of the energy potential (Booij et al., 1999; Ris et al., 1999; Tolman, 2009). The second objective centers on site-specific evaluation, where a comprehensive set of criteria encompassing physical, environmental, and socioeconomic factors such as bathymetry, habitat protections, and shipping

routes is developed to assess suitability, drawing on insights from studies like Defne et al. and data from the New Jersey Department of Environmental Protection (Haas et al., 2011; NJDEP, 2020). At last, what's the framework of policy and regulation that has been institutionalized, and what should developers consider to ensure environmentally friendly development?

1.4 Scope and Limitations

The geographic scope of this study encompasses the nearshore and offshore regions of the New Jersey coastline, extending to depths where wave and tidal installations become feasible. This range allows for a comprehensive evaluation of coastal areas where energy extraction technologies can be effectively deployed, balancing proximity to shore with sufficient water depth to support infrastructure.

The technological scope focuses exclusively on wave and tidal hydrokinetic energy, excluding other marine renewables such as offshore wind or ocean thermal energy conversion. Additionally, due to the significant environmental impact associated with traditional barrage-based tidal potential energy technology, such as habitat disruption and altered ecosystems, this approach is not considered in this study, aligning the research with more environmentally compatible tidal current technologies.

The accuracy of this study relies heavily on the availability and resolution of wave and tidal data, sourced from NOAA NDBC (2022) and NOAA CO-OPS (2022). Numerical modeling tools depend on assumptions about bathymetry and boundary conditions, which may introduce uncertainties in resource estimates due to potential inaccuracies in the input data. These constraints highlight the limitations inherent in modeling efforts when working with variable data quality.

Regulatory and environmental constraints shape the study's approach, with broad environmental data such as protected areas and shipping lanes overlaid for analysis. However, detailed ecological impact assessments or stakeholder engagement fall outside the immediate scope, reflecting the timeline and resource constraints of this study. These limitations may influence the precision of site-specific recommendations, underscoring the need for further investigation in future research phases.

2 Literature Study

2.1 Tidal Energy: Predictability, Resource Assessment, and Site Selection

Tidal energy, derived from the regular and predictable movement of seawater driven by the gravitational pull of the moon and the sun, offers a compelling alternative to more variable renewable sources such as wind and solar. As global energy demand, especially electricity consumption, continues to rise, the need for dependable renewable sources becomes increasingly acute (IEA, 2024). Tidal energy is especially attractive due to its inherent predictability; tidal cycles can be forecasted centuries in advance, providing an almost unrivaled level of temporal consistency (NOAA CO-OPS, 2024).

Historically, tidal energy extraction has been implemented primarily through tidal range systems, such as the La Rance Tidal Power Plant in France, which has been operational since 1960 with a capacity of 240 MW (EDF, n.d.). Such tidal energy systems that harness potential energy through dams or barrages involve constructing large barriers across estuaries or bays to capture the rise and fall of tides, generating power as water flows through turbines. However, these systems present several significant drawbacks. They require specific geographic conditions with high tidal ranges (typically over 5 meters), limiting viable sites to a few locations worldwide and excluding much of New Jersey's coastline. Construction costs are exorbitantly high, often in the billions, due to the scale of infrastructure needed, and maintenance is challenging because of corrosion and biofouling from marine environments (Chowdhury et al., 2020; OES-Environmental, 2020). Environmentally, barrages can severely disrupt ecosystems by altering water flow, salinity, and sediment distribution, leading to habitat loss for fish and birds, reduced oxygen levels, and potential harm to marine mammals from turbine blades or electromagnetic fields (Nash & Phoenix, 2017; OES-Environmental, 2020). Energy production is intermittent, dependent on tidal cycles, which may not align with peak demand, and the overall development has been slow due to insufficient research on long-term impacts (OES-Environmental, 2020).

Given these challenges, including high costs, environmental risks, and site limitations, this study does not consider traditional barrage-based tidal potential energy systems. Instead, we focus

exclusively on tidal current technology, also known as tidal hydrokinetic energy, which extracts kinetic energy from flowing tidal streams using underwater turbines. This approach offers greater flexibility, lower environmental disruption, and applicability to a wider range of coastal sites in New Jersey.

More recently, technological advances have spurred interest in tidal hydrokinetic energy, which harnesses the kinetic energy of moving water through tidal turbines or tidal energy converters (TECs) (Hardisty, 2009; Li et al., 2023). This evolution in technology is occurring against a backdrop of significant shifts in the global energy mix. Whereas fossil fuels once dominated electricity production, their share has been declining in recent years as renewables gain traction (IEA, 2024).

Assessing tidal energy potential involves a combination of observational data and sophisticated numerical modeling. Given the relative stability of tidal cycles, the kinetic energy approach has attracted attention due to its higher conversion efficiency and lower environmental impact (Neill et al., 2021; Defne et al., 2012). Quantifying tidal kinetic energy resources requires careful analysis of hydrodynamic data, including tidal current velocities, water depth, and the spatial distribution of tidal ranges. Various methods have been developed to assess these resources. Early methods, such as equations in earlier theoretical work and the flux method, provided preliminary estimates by calculating energy flux through cross-sectional areas of tidal channels. More recent approaches employ dynamic numerical models to simulate the complex hydrodynamics of tidal environments (Yang & Wang, 2020; Park et al., 2019). For instance, the power-limit analysis introduced by Garrett and Cummins has been used in bay/channel designs, while array ("farm") methods that evaluate the extraction potential of turbine fields are now prominent for larger-scale assessments (Garrett & Cummins, 2005; Nishino & Willden, 2012; Funke et al., 2014).

Modern hydrodynamic models, including 2D shallow-water models and 3D simulations (such as Delft3D and EFDC), have significantly advanced our ability to predict tidal flows and energy yields (Mohammadian et al., 2019; Hwang & Jo, 2019; Zou et al., 2024; Thiébot et al., 2020). Although 2D models offer the advantage of lower computational requirements, they often fail to capture vertical flow distributions accurately a critical factor for turbine placement and efficiency (Goward Brown et al., 2019). In contrast, 3D models provide a more detailed picture of the

complex interplay between tidal currents and bathymetry, but they require more extensive computational resources. For instance, 3D models have been shown to provide more accurate representations of the Koksoak estuary's hydrodynamics, leading to improved estimates of tidal power density (Mohammadian et al., 2019). As a result, many studies have adopted a hybrid approach, using 2D models for preliminary site screening and 3D models for detailed analysis in the most promising areas (Mohammadian et al., 2019; Espina-Valdés et al., 2019).

Nevertheless, these modeling approaches are not without limitations. One major issue is the trade-off between model resolution and computational cost. High-resolution 3D models require extensive computational resources and longer simulation times, which may not be feasible for large-scale, regional assessments (Goward Brown et al., 2019). As a result, many researchers have advocated for a tiered approach, where simpler two-dimensional (2D) models are used for initial screening and high-resolution 3D models are reserved for detailed analysis of the most promising sites (Espina-Valdés et al., 2019). Moreover, model accuracy can be compromised by uncertainties in input data, such as bathymetry and boundary conditions. In many coastal regions, including parts of the Mid-Atlantic, data may be outdated or of insufficient resolution, leading to uncertainties in simulated tidal currents and energy fluxes (Mohammadian et al., 2019; Hwang & Jo, 2019). Addressing these uncertainties requires not only improved data collection methods but also the development of robust calibration techniques that can reconcile model outputs with limited observational datasets.

Another critical challenge in tidal energy resource assessment is the variability in tidal current speeds and the distribution of turbine arrays on local hydrodynamics. For example, in regions where the peak tidal current speed barely exceeds 1 m/s, the minimum required for economically viable energy conversion, the presence of turbines should be carefully deployed to ensure an optimized or at least close-to-optimized configuration (Li et al., 2023). Therefore, high resolution of modeling and device-level analysis are required. While the technical potential of tidal energy is well recognized, its successful deployment hinges on a host of environmental and socioeconomic factors. One of the major advantages of tidal energy is its low environmental impact compared to other forms of renewable energy. The predictable nature of tidal cycles minimizes the risk of ecological disruption and offers the possibility of careful planning around sensitive marine habitats (OES-Environmental, 2020; Nash & Phoenix, 2017). However, even low-impact systems must be

designed with care to avoid unintended consequences, such as altering sediment transport or affecting local fisheries.

In assessing tidal energy projects, environmental constraints such as the presence of marine protected areas, benthic habitats, and navigation channels must be considered alongside hydrodynamic factors. Studies have demonstrated that while tidal turbines can operate with minimal disturbance, their placement in high-density ecological zones or busy shipping lanes may lead to conflicts and regulatory challenges (Hwang & Jo, 2019; Defne et al., 2012). Consequently, multi-criteria site selection frameworks that integrate technical, environmental, and socioeconomic data are essential for identifying optimal locations for tidal energy installations.

Socioeconomic factors also play a pivotal role in determining the feasibility of tidal projects. The proximity of potential sites to energy demand centers and existing grid infrastructure can greatly influence the overall project economics (Chowdhury et al., 2020). For instance, the coastal waters of New Jersey offer the dual advantage of moderate tidal ranges and relative closeness to large population centers. However, these benefits must be weighed against potential conflicts with recreational uses, commercial shipping, local fisheries, and environmental concerns. In this context, stakeholder engagement and regulatory alignment are as critical as technical feasibility (NJDEP, 2025). Several studies have attempted to integrate these diverse factors into comprehensive site selection models. For example, researchers have combined hydrodynamic modeling with GIS-based spatial analysis to evaluate candidate sites by overlaying physical data (tidal velocities, depth) with environmental constraints (protected areas, sensitive habitats) and human-use patterns (shipping lanes, coastal development) (Blunden & Bahaj, 2007). Such integrated approaches not only identify areas with high energy potential but also flag regions where environmental or socioeconomic conflicts might impede development.

The review of tidal energy literature reveals both significant progress and notable gaps. On the one hand, tidal energy's predictability and inherent reliability make it a highly attractive renewable resource. Advances in numerical modeling have enabled detailed assessments of tidal power potential, while device-level analysis combining hydrodynamic, environmental, and socioeconomic data offer promising frameworks for site selection (Neill et al., 2021; Blunden & Bahaj, 2007). On the other hand, the literature indicates that challenges remain in accurately

modeling complex tidal flows and in addressing the environmental and human-use implications of turbine installations.

For the New Jersey coastline, these issues should be considered. Although New Jersey is characterized by moderate tidal ranges and currents that are sufficient for energy extraction, the region also features dense coastal development, busy shipping lanes, and ecologically sensitive areas. Existing studies (e.g., Tang et al., 2014a; Defne et al., 2012) have highlighted the potential for marine renewable energy in the Mid-Atlantic but have not provided a comprehensive, integrated assessment that accounts for all relevant factors. In particular, there is a gap in the literature regarding the application of advanced 3D modeling techniques and GIS-based multi-criteria decision analysis for tidal energy site selection in this region.

Critical analysis of the existing literature indicates that while numerous studies have focused on the technical and hydrodynamic aspects of tidal energy, less attention has been paid to the comprehensive integration of these factors with environmental and socioeconomic considerations. For instance, most of the research on tidal modeling has been concentrated in regions such as the Black Sea, the Koksoak estuary, or European coastal areas (Mohammadian et al., 2019; Espina-Valdés et al., 2019), with relatively few studies applying these techniques in the context of the Mid-Atlantic or New Jersey. This regional gap is particularly concerning given that local bathymetry, tidal characteristics, and human-use patterns can significantly alter both the feasibility and the environmental impact of tidal installations. Furthermore, while studies have validated the performance of 2D and 3D models against observed tidal levels and currents (Goward Brown et al., 2019; Hwang & Jo, 2019), there is a paucity of research examining the long-term ecological effects of tidal turbine arrays. For example, research by Barbour and Bryden (2011) has indicated that slack tide periods when energy output drops to near zero may require supplementary energy storage systems to ensure grid stability. Yet, the implications of such storage solutions on local marine ecosystems and the overall sustainability of tidal projects remain underexplored.

Tidal energy stands out as a highly predictable and sustainable renewable resource that benefits from the regularity of tidal cycles and advances in numerical modeling. Despite its many advantages, significant challenges remain in terms of accurately assessing energy potential, addressing environmental impacts, and integrating socioeconomic factors into site selection

models. The literature reveals a strong foundation in hydrodynamic modeling techniques but also highlights the need for a more integrated approach that combines technical, environmental, and human factors, particularly in regions with complex coastal dynamics such as New Jersey.

This research underscores the importance of a comprehensive evaluation framework by synthesizing insights from a diverse range of studies. Such a framework will improve the precision of energy yield predictions and facilitate the selection of sites that balance economic viability with environmental sustainability and social acceptability. It is against this backdrop that the present study proposes a multi-faceted methodology, leveraging state-of-the-art tools and GIS-based spatial analysis to address the existing gaps in tidal energy site selection research. Notably, this methodology incorporates an unprecedented 100-meter grid resolution within Delft3D, significantly enhancing the accuracy of hydrodynamic simulations compared to traditional coarser grids. The present study seeks to address this gap by developing a high-fidelity framework that synthesizes advanced hydrodynamic modeling with environmental and socioeconomic assessments. By leveraging state-of-the-art tools such as Delft3D for detailed 3D simulations with the enhanced precision afforded by 100-meter grids and integrating these results with spatial analyses of marine protected areas, shipping lanes, and coastal infrastructure, the research aims to provide a robust evaluation of potential tidal energy sites along the New Jersey coast. Such an approach improves the accuracy of energy yield predictions and ensures that selected sites are environmentally sustainable and socially acceptable.

2.2 Survey of Existing Tidal Energy Resource Estimates in New Jersey

National-level assessments provide context for NJ's tidal resources within the broader U.S. East Coast. A comprehensive 2011 study by Georgia Tech Research Corporation, funded by the U.S. Department of Energy (DOE), developed a database and GIS tool to evaluate tidal stream energy across U.S. coastlines using the Regional Ocean Modeling System (ROMS) (Haas et al., 2011). The analysis identified "hotspots" with average current speed greater than 1 m/s, surface area larger than 0.5 km² depth greater than 5 m (Defne et al., 2012). Nationally, the theoretical available power from tidal streams totals 50.783 GW (Defne et al., 2012). On the East Coast, Maine and Massachusetts have significant hotspots.

The total theoretical power for NJ is estimated at 192 MW. More specifically, Delaware Bay was identified as a hotspot, contributing 331 MW when shared with Delaware; Great Egg Harbor Bay Inlet and Little Egg Inlet, as the next potential sites, were estimated to provide 6 MW and 5 MW, respectively; other identified hotspots include Barnegat Bay, Point Creek, Steelman Bay, Absecon Inlet, Corson Inlet, Hereford Inlet, and Cape May Inlet (Haas et al., 2011; Defne et al., 2012).

High-resolution modeling has been pivotal in refining NJ-specific estimates. A 2014 study by Tang et al. used the Finite Volume Coastal Ocean Model (FVCOM, version 2.7) along the Mid-Atlantic Bight (MAB), focusing on NJ coastlines (Tang et al., 2014a). The model incorporated bathymetry, coastlines, and tributaries, calibrated against data from 47 stations. Results indicate a total MHK energy flux in NJ nearshore regions of about 2.1 GW, with several sites exceeding 400 W/m² power density. This theoretical estimate is much larger than the national estimate, which is attributed to the different method of tidal power evaluation and resolution of the model (Tang et al., 2014a).

A companion 2014 report by Tang et al. conducted a thorough survey of NJ and neighboring coastlines, identifying 32 top sites with power density >250 W/m², of which 21 are in NJ covering 13 km² (Tang et al., 2014b). Power densities range from 250 to 1000 W/m² (peak velocities 1.26 –2.0 m/s), with sites like Chester Island, Pea Patch Island, Cape May Point, Absecon Inlet, Barnegat Light, and Sea Bright highlighted. Many are near bridges, ports, docks, or marinas (e.g., Carriage House Marina, Gateway Marina), facilitating integration with transportation infrastructure. The report recommended 20 primary sites based on success potential and value to NJ's marine transportation system (Tang et al., 2014b).

SLR emerges as a factor in NJ's tidal energy future, given its vulnerability to coastal flooding. Tang et al. (2014a) simulated SLR scenarios of 0.5 m and 1 m, finding increases in tidal energy by 21% and 43%, respectively, in NJ coastal waters. However, SLR reduces top sites along barrier islands facing the Atlantic while increasing them in Delaware Bay and River. Individual sites show varied responses: some disappear, others emerge, with changes in power density, area, and depth. This underscores the need for adaptive planning in resource assessments (Tang et al., 2014a).

2.3 Review of Tidal Energy Conversion Devices (TEC)

Tidal Energy Conversion (TEC) devices encompass a range of technologies designed to capture and convert the kinetic or potential energy from tidal flows into usable electricity, with classifications including barrages, lagoons, and stream-based hydrokinetic systems. Given the environmental and regulatory constraints outlined in previous sections, this review prioritizes hydrokinetic TEC devices that harness tidal currents without impoundment, such as horizontal-axis turbines (resembling underwater windmills), vertical-axis turbines, and cross-flow variants, which offer flexibility for deployment in New Jersey's estuaries and coastal channels. These devices operate by rotating blades in flowing water to drive generators, with efficiencies influenced by current velocities, rotor design, and site-specific hydrodynamics, providing a foundation for evaluating their feasibility in high-potential areas like Barnegat Inlet and Cape May.

Sabella: The Sabella D10, a pioneering 1 MW horizontal-axis tidal turbine featuring six blades and a fully submerged, seabed-mounted design, was deployed as a grid-connected demonstrator in France's Fromveur Passage off Ushant Island in 2015, becoming the nation's first operational tidal energy project supplying power to the local grid (Fig. 2.1 and 2.2). Extensive academic documentation supports its evaluation, encompassing both turbine performance and site-specific resource dynamics. Paboeuf et al. (2016) deliver a rigorous IEC-compliant power performance assessment in an OMAE proceedings paper, quantifying energy yields and operational efficiency under real-world tidal flows exceeding 3 m/s. Complementing this, Guillou et al. (2020) provide a comprehensive hydrodynamic review of the Fromveur Strait, modeling current velocities, turbulence, and wake dissipation to contextualize long-term yields and minimal environmental disruptions. As of October 2024, the D10 continues to operate reliably under Inyanga Marine Energy's stewardship.

Figure 2.1 The Sabella D10 tidal turbine, a full-scale demonstration device designed to harness tidal current energy in the Fromveur Passage, Ushant, France (https://www.oceanenergy-europe.eu/annual/sabella/).

Figure 2.2 Sabella D10" has a total height of 56 feet (17 meters), a rotor diameter of 33 feet (ten meters) and a weight of 450 metric tons (https://www.oceanenergy-europe.eu/annual/sabella/).

SeaGen: Deployed in Strangford Lough, Northern Ireland, this design stands as the most extensively studied full-scale, grid-connected single tidal turbine from an academic perspective, marking a milestone as the world's first commercial-scale tidal stream generator when commissioned in 2008 by Marine Current Turbines (now part of SIMEC Atlantis Energy) (Fig. 2.3) (Power-Technology, 2020; The Guardian, 2008; Atlantis Resources, 2015).Douglas et al. (2008) provide a rigorous life-cycle assessment (LCA), detailing energy and carbon payback metrics over its operational lifespan, establishing a benchmark for environmental sustainability. Complementing this, a comprehensive biological monitoring program is synthesized, integrating data from Strangford's multidisciplinary Environmental Monitoring Program to assess impacts on marine life, including collision risk, noise propagation, and habitat integrity (Royal Haskoning, 2011; Sparling et al., 2018). Together, these studies form a robust foundation for current consenting practices, offering critical baselines and mitigation strategies that inform the deployment of similar hydrokinetic technologies in high-potential sites.

Figure 2.3 The SeaGen tidal turbine installed in Strangford Lough, Northern Ireland, serving as one of the most studied full-scale, grid-connected tidal energy devices (https://en.wikipedia.org/wiki/SeaGen).

Eastern Scheldt storm-surge barrier Tidal Energy Project: The Tocardo turbines, integrated into the Eastern Scheldt storm-surge barrier in the Netherlands, exemplified a unique approach to tidal energy through barrier-integrated arrays, leveraging existing infrastructure to harness tidal flows with minimal additional environmental footprint (Fig. 2.4). De Fockert et al. (2023) offer a system-scale evaluation, analyzing the effects of tidal power extraction through the barrier's gates, providing insights into energy yield and flow dynamics under varying tidal conditions up to 2 m/s. Complementing this, O'Mahoney et al. (2020) integrate computational fluid dynamics (CFD) with field data to assess hydrodynamic impacts, turbine efficiency, and power production, highlighting the system's adaptability to complex coastal environments. Technical studies from Deltares further enhance the analysis, detailing advanced turbine control strategies and optimizing system performance, as documented in peer-reviewed reports (Deltares, 2018; Deltares, 2019). Collectively, these studies provide a robust evidentiary base for siting tidal energy arrays within major infrastructure and ecologically sensitive areas, offering valuable lessons for potential applications in New Jersey's coastal defenses, such as near bridge structures, as of September 19, 2025.

Figure 2.4 This installation is the largest tidal energy project in the Netherlands as well as the world's largest commercial tidal installation of five turbines in an array (https://www.tidalbridge.com/projects/tidal-power-plant-larantuka-indonesia-2/).

O2: Floating tidal platforms, notably exemplified by Orbital Marine Power's O2 lineage (Fig. 2.5), are increasingly supported by a robust academic foundation, drawing from full-scale field performance and load research on its predecessor, the SR2000. Field testing, such as Jeffcoate et al. (2018), detail blade load dynamics and operational behavior under challenging winter sea states with wave heights exceeding 2 meters and tidal currents up to 2.5 m/s, showcasing the platform's resilience and energy capture efficiency in Scotland's turbulent waters. Recent reviews, including Gu et al. (2024), chart the maturation of large-scale marine current systems and arrays, positioning floating horizontal-axis tidal turbines (HATTs) as operationally efficient and maintenance-friendly alternatives to traditional monopile foundations. This evolving technology offers promising scalability for New Jersey's offshore sites, such as the central-eastern shelf, where dynamic conditions and depth constraints align with its deployment potential as of September 19, 2025.
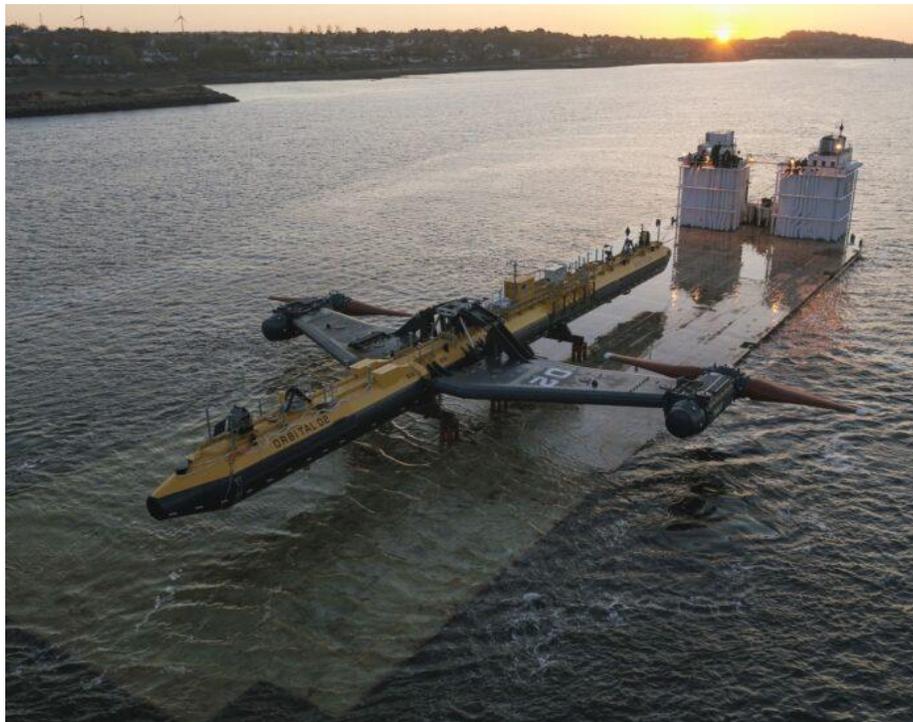

Figure 2.5 Orbital Marine Power's O2 is a floating tidal platform
(https://www.orbitalmarine.com/o2/).

Figure 2.6 October 1, 2020 - Verdant Power's RITE project made the journey from New Jersey to New York City's East River with co-funding from the U.S. Department of Energy's Power and Technologies Office and the New York State Energy Research and Deployment Authority (https://verdantpower.com/rite/).

Verdant's Gen5: Urban-channel deployments provide valuable insights into licensing and metering challenges within built environments, as demonstrated by Verdant Power's Roosevelt Island Tidal Energy (RITE) project in New York's East River (Fig. 2.6). Gunawan et al. (2014) offer a comprehensive academic resource assessment, detailing the site's tidal flow characteristics and energy potential with current velocities reaching 2.5 m/s. Subsequent research, including Chawdhary et al. (2018), employs high-fidelity large eddy simulation (LES) to analyze a 30-turbine TriFrame array, shedding light on wake interactions and array performance. More recently, Murray et al. (2023) contribute *Energies* journal studies on instrumentation and data acquisition (DAQ) systems, focusing on thermoplastic blade durability and field measurements, enhancing understanding of operational reliability. Together, these peer-reviewed studies establish critical baselines for flow characterization, wake dynamics, and instrumentation deployment in urban tidal straits, offering relevant guidance for similar constrained environments in New Jersey, such as the Hudson River.

HydroQuest: Full-scale vertical-axis tidal turbine (VATT) concepts are less common, but the HydroQuest Ocean program at the Paimpol-Bréhat test site in France has produced significant

academic insights into their performance and behavior (Fig. 2.7). Moreau et al. (2022, 2023) detail a comprehensive study, bridging laboratory experiments to field-scale observations for a ducted twin-VATT system, analyzing its response to wave conditions and twin-rotor hydrodynamics. Their research highlights the influence of sea states on structural loads and energy output, providing valuable data for siting these turbines in fetch-exposed channels.

Figure 2.7 The HydroQuest Ocean vertical-axis tidal turbine, designed to capture energy efficiently from tidal currents in marine environments (https://en.wikipedia.org/wiki/HydroQuest).

Minesto: Kite-based cross-current systems, exemplified by Minesto's innovative design (Fig. 2.8), are gaining traction with a growing body of academic research. Advanced modeling techniques, including large-eddy simulations and actuator-line methods, have been tailored to analyze the wake dynamics of moving kites, as detailed by Fredriksson et al. (2021), offering insights into their fluid-structure interactions. Additionally, hydrodynamic and control studies from the PowerKite and Horizon projects explore power take-off (PTO) optimization and flightpath modeling, providing critical guidance for deploying these systems in lower-velocity tidal regimes.
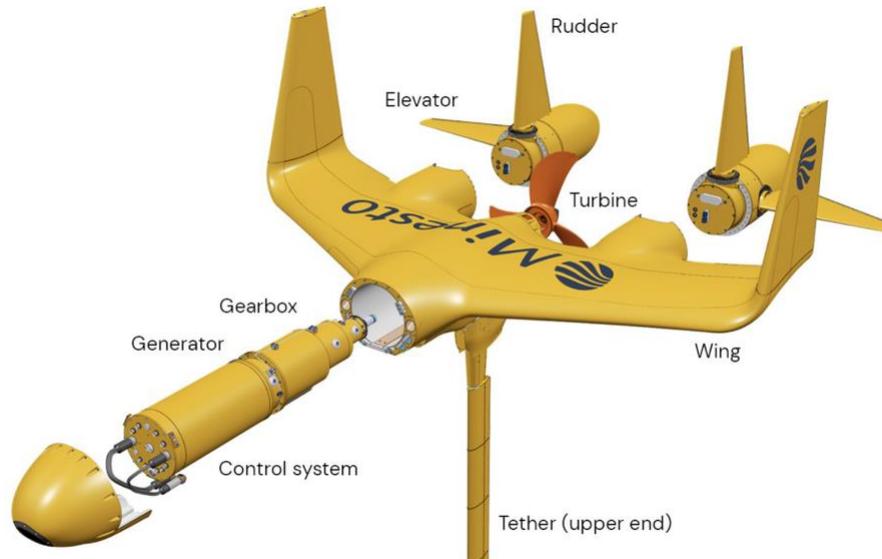
Figure 2.8 The Minesto kite-based cross-current tidal energy system, which uses a tether and control surfaces to generate power in lower-velocity tidal flows (https://minesto.com/our-technology/).

All of the TEC technologies reviewed are summarized in Table 2.1. This table provides a concise overview of each technology's name, key pros and cons, current "Technology Readiness Level (TRL)", "Commercialization Level", and notable locations where the technology has been developed or deployed.

Name	Pros	Cons	TRL	Commercialization Level	Locations
Sabella D10	High efficiency in strong currents (>3 m/s), reliable grid connection, minimal environmental footprint with seabed mounting.	High installation costs, limited to deep, high-velocity sites, potential noise/EMF impacts on marine life.	7-8 (Demonstrated at full scale with ongoing optimization).	Pre-commercial; pilot stage with Inyanga Marine Energy, no large-scale deployment yet.	Fromveur Passage, Ushant, France (operational demonstrator).
SeaGen	Well-studied with proven LCA benefits, high energy yield (1.2 MW), robust	Expensive maintenance, noise and habitat disruption risks, site-	8 (Full-scale operational with extensive monitoring).	Pre-commercial; single-unit demonstration, no widespread commercial arrays.	Strangford Lough, Northern Ireland (first commercial-scale tidal turbine).

	collision risk data.	specific to strong tidal flows.			
Tocardo (Eastern Scheldt Barrier)	Leverages existing infrastructure, dual benefit of flood protection and energy, efficient in moderate currents.	Complex integration with barriers, sediment and flooding risks, high initial costs.	6-7 (Pilot integration with ongoing technical studies).	Pre-commercial; limited to specific barrier sites, not broadly deployed.	Eastern Scheldt storm-surge barrier, Netherlands (pilot project).
Orbital O2 (Floating Tidal Platform)	O&M-efficient due to floating design, adaptable to variable depths, resilient in energetic sea states.	Higher installation complexity, potential collision risks with marine life, less studied for arrays.	6-7 (Full-scale testing with SR2000, O2 in development).	Pre-commercial; prototype stage with ongoing field trials.	Orkney, Scotland (EMEC test site for SR2000/O2 prototypes).
Verdant Power RITE (Urban-Channel)	Suitable for urban channels, innovative TriFrame array design, extensive flow/wake data.	Licensing challenges in built environments, noise/EMF concerns, limited scalability.	7 (Demonstrated with multiple turbines, refining instrumentation).	Pre-commercial; pilot in East River, no commercial scale yet.	East River, New York City, USA (RITE project demonstration).
HydroQuest Ocean (Vertical-Axis)	Dual-rotor design enhances stability, adaptable to wave-exposed sites, potential for high energy capture.	Limited full-scale data, higher load risks in rough seas, complex control systems.	6-7 (Pilot testing with scaling studies underway).	Pre-commercial; early demonstration phase, not yet commercialized.	Paimpol-Bréhat test site, Brittany, France (operational pilot).
Minesto (Kite-Based Cross-Current)	Efficient in low-velocity regimes (<2 m/s), innovative kite design reduces costs, scalable arrays possible.	Early-stage technology, flightpath control challenges, potential wildlife collision risks.	5-6 (Prototype testing with simulations, not yet full-scale operational).	Pre-commercial; pilot projects in development, no commercial deployment.	Holyhead Deep, Wales, UK (test site); planned sites in Faroe Islands.

Table 2.1 Summary of TEC technology.

2.4 Wave Energy: Potential, Challenges, and Modeling

Wave energy represents one of the most promising avenues among renewable energy sources owing to its high-power density and vast global potential. The ability of ocean waves to concentrate energy in many instances exceeding that of wind and solar per unit area has been a primary motivation for researchers and engineers (Falcão, 2010; Mørk et al., 2010). Globally, oceans hold immense kinetic energy; theoretical assessments estimate that the U.S. continental shelf alone may harbor up to 1851 TWh/year of wave energy, with a technical potential of around 899 TWh/year (DOE, 2015; Ahn et al., 2019). Despite these promising Figs, wave energy conversion systems (WECSs) face critical challenges that impede commercialization, such as high costs, low technological maturity, and harsh marine conditions (Aderinto & Li, 2019).

One of the foremost barriers to widespread adoption of wave energy is its high levelized cost of energy (LCOE), a measure of the average cost to generate electricity over the lifetime of a power plant. Estimates for WECSs range between 0.18 and 0.87 USD/kWh, substantially higher than those for solar (0.06–0.38 USD/kWh) and offshore wind (0.10–0.56 USD/kWh) (Guo et al., 2023). The elevated LCOE is largely due to the severe operational environment that wave devices must withstand. These devices encounter extreme wave forces, corrosion, and other forms of marine degradation that drive up both capital and maintenance expenses. Additionally, the lack of a universally accepted design in contrast to the relatively standardized designs in wind and solar technologies results in a proliferation of prototypes without clear consensus on optimal configurations (Guo et al., 2023).

Furthermore, the cost challenge is exacerbated by issues of grid connectivity and energy storage, which are essentially due to the intermittency of wave energy. While the predictability of wave can span several days, it is still challenging to implement robust storage solutions or grid management strategies to ensure steady supply due to short-term uncertainties (Rusu & Onea, 2015). To compete with conventional fossil fuels and other renewables, research must focus on technological improvements and reducing costs through enhanced device durability and more efficient maintenance practices. Accurate modeling of wave energy resources is critical for site selection, resource assessments, and the design of efficient conversion systems. Traditionally, the estimation of wave energy potential has relied on parameters such as significant wave height (Hs)

and mean wave period (Tm), which together offer a measure of the total energy content of waves (Holthuijsen, 2007; Reguero et al., 2015). However, while valuable, these parameters do not fully capture the complex spectral distribution of wave energy, including the partitioning between wind-generated seas, swell, and directional energy fluxes (Portilla et al., 2009; Van Vledder & Akpınar, 2016).

The spectral characteristics of waves are crucial for understanding how energy is distributed across different frequency bands and directions. As Holthuijsen (2007) and Maisondieu & Le Boulluec (2016) note, wave spectra are integral not only to energy assessments but also to the design of marine structures, including ships and coastal defenses. For wave energy converters, detailed spectral analysis can inform the design of devices that are tuned to the predominant wave frequencies at a particular site. Unfortunately, observational data often remain limited both spatially and temporally, highlighting the importance of numerical models such as SWAN (Simulating WAves Nearshore) (Booij et al., 1999; Ris et al., 1999) and WWIII (WaveWatch III) (Tolman, 2009). The SWAN model, in particular, has been validated in various regional studies from the Black Sea to the Mediterranean and is widely used to simulate nearshore waves (Akpınar et al., 2012; Arkhipkin et al., 2014; Van Vledder & Akpınar, 2016).

The accuracy of wave models is of paramount importance for site selection studies. In regions like New Jersey, where ocean waves are moderate but consistent, even small errors in modeling can significantly influence the predicted energy yield and, consequently, the economic feasibility of a project. Researchers have suggested that coupling high-resolution numerical models with in situ measurements could provide a more robust framework for site assessment (Contardo et al., 2018). While technical and economic challenges dominate the discussion around wave energy, environmental and site-specific factors are equally critical, especially in the context of New Jersey's coastal waters. The local waves are influenced by both local wind patterns and distant storm systems. For example, Gaudet et al. (2022) have demonstrated that the Mid-Atlantic region exhibits unique wave characteristics that need localized assessments rather than a direct extrapolation from global studies. Furthermore, environmental constraints such as marine habitats, coastal erosion, and protected areas must be integrated into the evaluation process to ensure that energy development does not adversely affect ecological systems (Defne et al., 2012; NJDEP STAP, 2019). In addition to ecological considerations, artificial factors such as navigation

channels, coastal community impacts, and regulatory frameworks are vital in site selection. High-energy zones might be technically attractive, but if they overlap with major shipping routes or protected areas, the feasibility of installation diminishes. Incorporating multi-criteria analysis that balances energy potential with environmental and socioeconomic impacts is therefore essential. Studies have begun to explore such integrated approaches, proposing frameworks that combine physical wave data with spatial analysis using geographic information systems (GIS) (Azzellino et al., 2013; Azzellino et al., 2019).

In New Jersey, the proximity of potential sites to large population centers and existing energy infrastructure adds another layer of complexity but also opportunities. The relatively moderate wave heights, while promising, must be weighed against the cost of connecting offshore installations to the onshore grid and mitigating any adverse visual or ecological impacts. Thus, site-specific studies in this region must not only evaluate the raw energy potential but also account for local environmental constraints and infrastructural compatibility.

In summary, the literature on wave energy illustrates a field of high potential yet significant technical and economic hurdles. On the technical side, while models like SWAN have advanced our understanding of waves, their limitations in spectral resolution and directional accuracy are nontrivial (Ris et al., 1999; Björkqvist et al., 2020). Economically, the high LCOE underscores the need for innovative design improvements and cost reduction strategies (Guo et al., 2023). Environmentally, a critical gap exists in the integration of localized assessments with broader ecological and socioeconomic criteria—an area that is particularly underexplored for regions like New Jersey.

2.5 Survey of Existing Wave Energy Resource Estimates in New Jersey

Wave energy resource assessments are more abundant in the literature, with over 100 studies published globally in the past two decades. Third-generation spectral wave models such as SWAN, WaveWatch III (WW3), and MIKE 21 SW dominate these efforts, often configured with nested grids to capture both deep-water swell propagation and nearshore transformation processes. High-fidelity studies typically employ nearshore resolutions finer than 250 m, extending to 100 m or less in complex coastal settings, and run multi-year simulations to capture interannual variability.

These studies highlight the critical importance of accurate wind forcing, spectral resolution, and bathymetric detail in reproducing wave characteristics. Calibration against buoy observations, particularly for storm-driven events, has been shown to significantly improve model skill. However, much of the existing U.S. East Coast work has been coarse in spatial resolution or limited in temporal coverage, resulting in underestimation of localized energy hotspots, especially along barrier-island coasts and shoaling shelves.

According to national assessments by the U.S. Department of Energy and the National Renewable Energy Laboratory (NREL), the total available wave energy resource along the U.S. continental shelf edge is estimated at 2,640 terawatt-hours per year (TWh/yr), with the East Coast contributing 240 TWh/yr as part of a broader marine hydrokinetic potential. The technically recoverable portion, assuming a capacity packing density of 15 megawatts per kilometer of coastline, stands at 1,170 TWh/yr nationally and 160 TWh/yr for the East Coast, highlighting the region's moderate wave energy compared to higher-resource areas like Alaska (620 TWh/yr recoverable) or the West Coast (250 TWh/yr). These estimates are derived from hindcast models like WaveWatch III, covering over 42,000 grid points and accounting for factors such as wave refraction and seasonal variability, with the East Coast showing average power densities influenced by northerly wave directions and inner-shelf enhancements of 65-75% in normally-directed flux (Jacobson, Hagerman & Scott, 2011; Kilcher et al., 2021).

A 2021 study by Ahn et al. (2021) further characterizes nearshore wave energy along the East Coast, including the Mid-Atlantic, using a 32-year (1979–2010) high-resolution Simulating Waves Nearshore (SWAN) model hindcast at 200 m spatial resolution, delineating eight wave climate regions based on spatial trends in resource attributes like omnidirectional wave power, significant wave height, and directionality; it notes relatively low temporal variability and potentially lower capital and operation costs compared to more energetic regions, though specific numerical estimates for New Jersey are not detailed. Regional studies, such as Defne et al. (2009), focused on wave power along the southeastern Atlantic coast but indirectly informed tidal assessments by highlighting energy densities in estuaries.

For New Jersey specifically, as part of the Mid-Atlantic subregion, the annual available wave energy is estimated at 14 TWh/yr along the outer continental shelf (200-meter depth contour) and

8 TWh/yr along the inner shelf (50-meter depth contour), with recoverable percentages ranging from 60-94% depending on packing densities of 10-20 MW/km, as per the 2011 Electric Power Research Institute (EPRI) assessment (Jacobson, Hagerman & Scott, 2011; Navigant Consulting, 2012). Local measurements from NOAA buoy station 44009 off Cape May indicate an average wave power density of approximately 6.76 kilowatts per meter (kW/m) based on observed data, though models slightly underpredict at 4.70 kW/m, reflecting New Jersey's modest but viable nearshore resource suitable for wave energy converters (NDBC Station 44009 page; Rutgers/UD resources using 44009 for validation). An earlier 2004 New Jersey Renewable Energy Market Assessment notes a theoretical potential driven by the state's 1,792 statute miles of tidal shoreline, with an average wave power of around 30 kW per meter of crest length, though it screened wave energy as having limited near-term economic viability due to high costs (10–25 ¢/kWh for 10–60 MW projects) and inadequate resources for significant development by 2008, compared to more favorable renewables like wind and solar (Navigant Consulting, 2004). State-level studies and legislative initiatives, such as bills advancing wave and tidal energy research, emphasize the need for further high-resolution assessments, but these national and regional Figs position New Jersey's potential within the East Coast's overall 200 TWh/yr available at the outer shelf (DiFilippo, 2022).

This review reveals that although the global body of research on wave energy is extensive, there is a pressing need for studies that synthesize high fidelity numerical modeling with practical, site-specific evaluations. Specifically, in the context of the New Jersey coastline, the current literature has not adequately addressed how local wave characteristics interact with regional environmental constraints to determine site suitability. This gap is a major motivation for the present study, which seeks to integrate technical, environmental, and socioeconomic criteria into a unified wave energy site selection framework.

2.6 Review of Wave Energy Conversion Devices (WEC)

Wave Energy Conversion (WEC) devices represent a diverse array of technologies designed to capture the kinetic and potential energy from ocean waves, offering a renewable energy resource along New Jersey's extensive coastline. This section reviews the primary WEC categories—point absorbers, oscillating water columns, attenuators, and overtopping devices—focusing on their operational principles and suitability for the state's wave energy corridor, characterized by median

annual power densities of 8–10 kW/m along the central-eastern shelf. With a focus on devices that can withstand the region's dynamic wave conditions and shallow nearshore environments, this analysis draws on field performance data and modeling studies to evaluate their potential for integration into New Jersey's renewable energy framework.

OWC: An Oscillating Water Column (OWC) is a type of wave energy converter that operates on a simple principle: it uses the vertical motion of waves to compress and decompress a pocket of air. This air, in turn, drives a turbine that is connected to a generator to produce electricity. This technology can be integrated into existing coastal structures or deployed as a floating device farther offshore.

For onshore applications, two full-scale OWC plants stand out as classic examples in the field. The Mutriku plant in the Basque Country is particularly significant because it has provided the most extensive, long-term, grid-connected dataset in academic literature (Fig. 5.8). The foundational engineering for this breakwater-integrated plant was first detailed by Torre-Enciso et al. (2009), and more recent studies by Lopez-Mendia et al. (2025) and Carreño-Madinabeitia et al. (2024) have explored operational improvements and long-term production strategies in the face of a changing wave climate. Another notable reference is the Islay LIMPET plant, whose hydrodynamics and shallow-water performance were thoroughly analyzed by Heath et al. (2001) and Folley & Whittaker (2002). Similarly, the Pico OWC plant has a rare, comprehensive technical review from Falcão (2020) that chronicles its entire operational life, from its initial design and subsequent retrofits to its overall availability and the crucial lessons learned from integrating such a system into civil structures (Fig. 5.9).

Figure 5.8 The Mutriku wave power plant (https://tethys.pnnl.gov/project-sites/mutriku-wave-power-plant)

Figure 5.9 Back view of the 400 kW OWC plant on the island of Pico, Azores, Portugal, 1999 (https://tethys.pnnl.gov/project-sites/pico-power-plant).

The development of "floating OWC" technology has been significantly advanced by controlled-environment experiments and extensive sea trials. A prime example is OceanEnergy's OE Buoy, which utilizes a backward-bent-duct OWC (BBDB) design (Fig. 5.10). Research on this technology, often presented at conferences like OES/ICOE and documented in later journal articles,

analyzes its unique hydrodynamic characteristics and models its motion and performance. This work is essential for informing critical design decisions, such as the best mooring layout and how to tune the power take-off (PTO) system for optimal energy extraction at different sites, including those in the challenging waters of the North Atlantic. For instance, experimental studies from ICOE 2010 and subsequent modeling by Sheng et al. (2019) have been instrumental in this progress.

Figure 5.10 The prototype of BBDB (the OE Buoy) equipped with a Wells turbine being tested in Galway Bay, Ireland, about 2008 (https://tethys.pnnl.gov/project-sites/testing-ocean-energy-buoy-galway-bay-ireland).

Floating OWC progress is supported by controlled-environment and sea-trial-oriented papers on OceanEnergy's OE Buoy (a backward-bent-duct OWC). OES/ICOE proceedings and subsequent journal work analyse hydrodynamic characteristics and motion/performance modelling for BBDB-type floaters, informing mooring layout and PTO tuning for North-Atlantic sites. See, for example, ICOE 2010 experimental studies and later modelling by Sheng et al. (2019).

Point Absorber: A point absorber is a type of wave energy converter that is small relative to the wavelength of the waves it's meant to absorb. It typically operates by "heaving," or moving up and down with the waves, and is designed to capture energy from all directions. The most advanced examples of this technology, such as the devices developed by CorPower (Fig. 5.11), use phase-controlled systems. This means that the device's motion is actively timed to be in sync with the incoming waves, allowing it to absorb more energy than if it were simply passively bobbing.

Figure 5.11 The CorPower Ocean wave energy converter, a point absorber device designed to harness the power of ocean waves for renewable energy generation (https://corpowerocean.com/).

The most cited academic evidence for these lightweight, phase-controlled buoys comes from rigorous "tank-to-field" testing programs. These programs start with controlled experiments in wave tanks and move on to real-world deployment at sea. For example, Todalshaug et al. (2016) presented comprehensive testing and validation of the inherent phase-control mechanism itself. Looking beyond just the technical performance, Pennock et al. (2022) provided a crucial life-cycle assessment (LCA) of a phase-controlled point-absorber array. Their work connected specific design choices to the overall environmental footprint of the technology, offering valuable data for comparing its impact with other renewable energy sources when deciding where to site new projects.

Attenuators / Hinged Rafts: An attenuator is a type of wave energy converter that operates parallel to the direction of wave travel. A typical design is consist of a long, segmented buoyant device floating on the surface of the water (Fig. 5.12). As a wave passes along its length, the segments flex and hinge, and this relative motion is used to drive a power take-off (PTO) system to generate electricity.

The Pelamis device remains the classic example of this technology and is extensively covered in academic literature. For instance, Henderson (2006) provided a detailed look at its unique hydraulic PTO architecture and control systems. In later research, Thomson et al. (2018) performed a full life-cycle assessment (LCA), which provided valuable data on its techno-environmental metrics. These types of studies give crucial, "bankable" information on survivability, fatigue, and potential cost reductions, which are now being used to create more modern models for wave energy arrays.
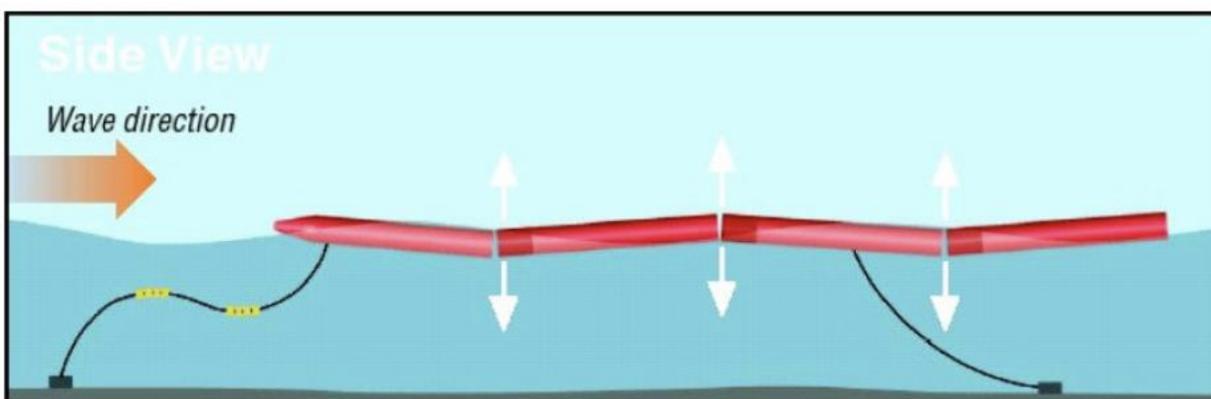

Figure 5.12 The Pelamis wave energy converter, an attenuator-type device that generates power by capturing energy from the motion of ocean waves along its articulated segments (https://en.wikipedia.org/wiki/Pelamis_Wave_Energy_Converter)

Oscillating-Surge Flaps (OWSCs): Oscillating-surge flaps, also known as oscillating wave surge converters (OWSCs), are devices that capture energy from the horizontal movement of waves with giant paddles or flaps that are hinged at the bottom and anchored to the seabed. As waves travel toward the shore, the flap is activated to generate power.

There are two main lines of evidence that have shaped our understanding of this technology. First, a body of work has focused on the hydrodynamics and wave-structure interaction of nearshore flaps, using everything from small-scale models to full-scale prototypes. Research like that from Wei et al. (2015) has been critical in defining how these devices capture energy and how they handle the immense forces from waves. Second, full-scale deployment programs, such as the Oyster program, have produced a wealth of data. Papers like those by O'Boyle et al. (2015) and

Karan et al. (2020) have synthesized this prototype data and conducted life-cycle assessments, documenting the evolution of the device's design. Together, these two areas of study have helped establish the ideal conditions for these surge devices, including the required water depth and nearshore wave climate, as well as influencing their overall structural design.

Overtopping Device: The Wave Dragon is a seminal example of an overtopping device, a technology that captures wave energy by allowing waves to flow over a ramp and into an elevated reservoir. The potential energy of the collected water is then converted into electricity as it returns to the sea through hydroturbines (Fig. 5.13). Research on this technology is well-documented, with studies providing critical insights into its operational characteristics. For example, Parmeggiani et al. (2013) reported on mooring design experiments for a 1.5 MW demonstrator at the DanWEC site. Their work quantified tension-reduction strategies and the device's response to extreme sea states, establishing key survivability criteria essential for deploying such systems in exposed maritime locations.
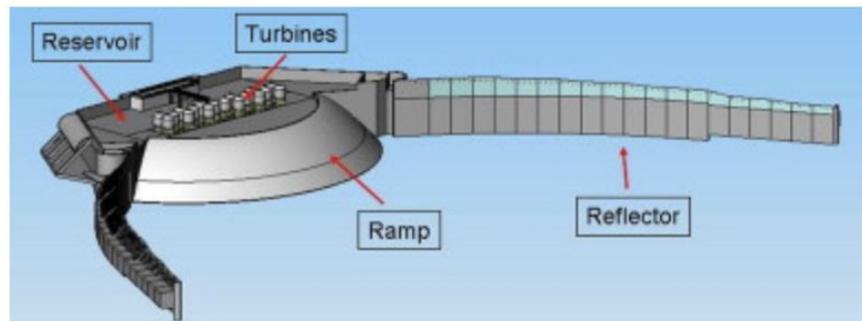

Figure 5.13 A schematic of an overtopping wave energy converter, illustrating its key components, including the reflector, ramp, reservoir, and turbines (adapted from Tedd et al., 2007).

Onshore Floater: Eco Wave Power (EWP) has developed a unique wave energy converter that attaches to existing marine structures like breakwaters, jetties, or seawalls (Fig. 5.14). The system uses lightweight floaters that rise and fall with the waves, driving hydraulic cylinders to create pressure. This pressure is then used to push a biodegradable fluid into onshore accumulators. The pressurized fluid is later released through a hydraulic motor and generator, which converts the motion into electricity that's then sent to the grid via an inverter. This design keeps all the sensitive

power take-off (PTO) equipment on land, which significantly reduces the risk of corrosion, simplifies maintenance, and lowers operational costs.

This technology has a proven track record with multi-year grid-connected experience in Gibraltar from 2016 to 2022. It also achieved its first grid connection at the EWP-EDF One station in Jaffa Port, Israel, in 2023. More recently, the technology is advancing in the U.S. at AltaSea in the Port of Los Angeles, where eight floaters and the onshore conversion unit were installed in 2025 under a USACE Nationwide Permit.

Figure 5.14 A nearshore wave energy converter deployed by Gibraltar's National Electric Company, designed to capture energy from breaking waves along the coastline (https://tethys.pnnl.gov/project-sites/eco-wave-power-wave-energy-power-station-gibraltar).

Other Technology: Another class of wave energy converters uses pressure-differential membranes, and a prominent example is Bombora's mWave. This technology is essentially a large, air-filled rubber membrane submerged on the seabed. As waves pass over it, the change in pressure causes the membrane to inflate and deflate. This motion pumps air through a turbine, which then generates electricity. Research on the mWave, such as papers by Algie et al. (2017) and Milani et al. (2023), focuses on both predictive models and experimental data. This work is particularly

useful for determining ideal nearshore locations (typically in 8–20 meters of water) and for optimizing the spacing of multiple devices in an array.

A different approach is the rotating-mass hull, exemplified by the Wello Penguin concept. This technology involves a floating device with an internal rotating mass. The motion of the waves causes the device to roll, and this rotational energy is transferred to a gyroscope-like internal mass. The slow rotation of the hull is converted into a high-speed rotation of the internal mass, which in turn drives a generator. Although these are not tied to a single, large-scale deployment report, reviews and PTO-specific papers (e.g., Amir et al., 2015; Crowley et al., 2018) provide academically vetted discussions on the core principles and design trade-offs. They delve into topics like control strategies and the long-term durability of these internal-mass converters.

All of the WEC technologies reviewed—including point absorbers, oscillating water columns, attenuators, oscillating surge flaps, overtopping devices, and alternative PTO concepts are summarized in Table 2.2. This table provides a concise overview of each technology's name, its classification, key pros and cons, current "Technology Readiness Level (TRL)", "commercialization status", and notable locations where the technology has been developed or deployed.

Name	Technology Class	Pros	Cons	TRL	Commercialization Level	Key Locations
Point Absorber	Heaving Buoy	Captures energy from all wave directions. Scalable and can be deployed in arrays.	High risk from extreme weather. High costs due to complex mooring and power cables.	7–8	Early commercial stage	Varies; typically offshore in deep water. e.g., CorPower (Portugal/Sweden).
Oscillating Water Column (OWC)	Attenuator/Terminator	Simple design with few moving parts in the water. Can be integrated into existing coastal structures.	Lower efficiency due to bidirectional air flow. High initial construction costs for shoreline installations.	7–8	Early commercial stage	Mutriku (Spain), Pico (Portugal), Islay (Scotland).
Attenuator / Hinged Raft	Attenuator	Operates parallel to waves,	Complex segmented structure.	5–6	Late-stage R&D	Former Pelamis

		making it less sensitive to direction. Can absorb energy from a wide range of wavelengths.	Requires strong, multi-point mooring and is susceptible to fatigue.			project (Portugal).
Oscillating Surge Flap	Terminator	Efficient in nearshore environments with strong horizontal wave surge. Less visible from shore.	Fixed to the seabed, limiting deployment depth. High structural loads from wave forces.	5–6	Late-stage R&D	Oyster project (Scotland).
Overtopping Device	Overtopping	Converts wave energy into potential energy, allowing for consistent power generation. The PTO is located in a protected reservoir.	Large structure with high capital costs. Performance depends on high and consistent wave energy.	5–6	Late-stage R&D	Wave Dragon demonstrator (Denmark).
Pressure-Differential Membrane	Submerged	Completely submerged, reducing visual impact and vulnerability to storms. PTO is on land or protected.	Requires specific seabed conditions for installation. Sensitive to biofouling.	5–6	Late-stage R&D	Bombora mWave (Spain).
Rotating-Mass Hull	Floating Body	Internal PTO is protected from the corrosive marine environment. Can operate far from shore.	Complex internal mechanisms. May have lower power capture than other concepts.	5–6	Late-stage R&D	Wello Penguin (Finland/Scotland).
Shore-Attached (EWP)	Shore-Attached	Lowers costs by attaching to existing infrastructure. PTO is on land, simplifying maintenance.	Performance is dependent on local harbor geometry and wave climate. Limited to specific coastal sites.	7–8	Early commercial stage	Gibraltar, Jaffa Port (Israel), Port of Los Angeles (USA).

Table 2.2 The summary of WEC technology

In summary, the wave and tidal energy literature point toward significant potential in marine renewables. However, common challenges such as high-levelized cost of energy, modeling limitations, and the need to integrate environmental and socioeconomic criteria persist in both fields, highlighting the need to advance the resource assessment from theoretical to capturable estimates. For tidal energy, the emphasis is on robust hydrodynamic modeling and integrated site selection that factors in ecological, regulatory, and community concerns. For wave energy, the critical need is for improved spectral modeling and localized site assessments that consider coastal constraints. In addition, both require specific device technology to be involved for accurate and practical estimates. The integrated review presented above also highlights that while research exists on the technical aspects of wave and tidal energy, the application of these insights to the specific context of the New Jersey coastline remains limited. This gap motivates the present study, which aims to develop a unified, high-fidelity framework for the systematic evaluation of marine renewable energy potential with the context of device technology. By addressing both the technical and non-technical dimensions of site selection and by employing high-fidelity models to capture fine-scale hydrodynamic variations, this research seeks to advance the state-of-the-art in marine renewable energy assessments and contribute valuable insights for policymakers and developers in New Jersey.

3 Tidal Energy Assessment

3.1 Numerical Model Specification

3.1.1 Model Selection

One of the key modeling decisions in this study was the selection of Delft3D as the numerical model for tidal energy assessment. Delft3D is a widely used hydrodynamic modeling tool capable of simulating coastal circulation, tidal dynamics, and sediment transport in structured grid environments. Delft3D was selected for this study due to its proven reliability in simulating shallow-water tidal hydrodynamics and its structured curvilinear grid approach, which allows for high spatial resolution near coastlines while optimizing computational efficiency.

3.1.2 Computational Domain and Grid

The model domain was designed to encompass the entire New Jersey coastline, stretching from Delaware Bay in the south to the New York Bight in the north, and extending up to approximately 300 kilometers offshore. This coverage ensures the capture of the full range of tidal influences, including interactions with adjacent water bodies like the Atlantic Ocean and the Delaware River estuary. The offshore extension is necessary to simulate the transition from deep ocean to shallow coastal waters, where tidal energy is most accessible for extraction.

High-quality data inputs are fundamental to the model's reliability. Bathymetry data were obtained from the CoNED and GEBCO databases (Danielson, J.J, et al, 2016; Weatherall, P. et al, 2015). These data were interpolated onto the Delft3D model grid using a bilinear interpolation method, ensuring an accurate representation of underwater topography. This step is crucial for capturing depth variations, which influence tidal wave propagation and current velocities, particularly in shallow coastal areas where bathymetric gradients significantly impact energy dynamics. The bathymetry is shown in Fig 3.1.
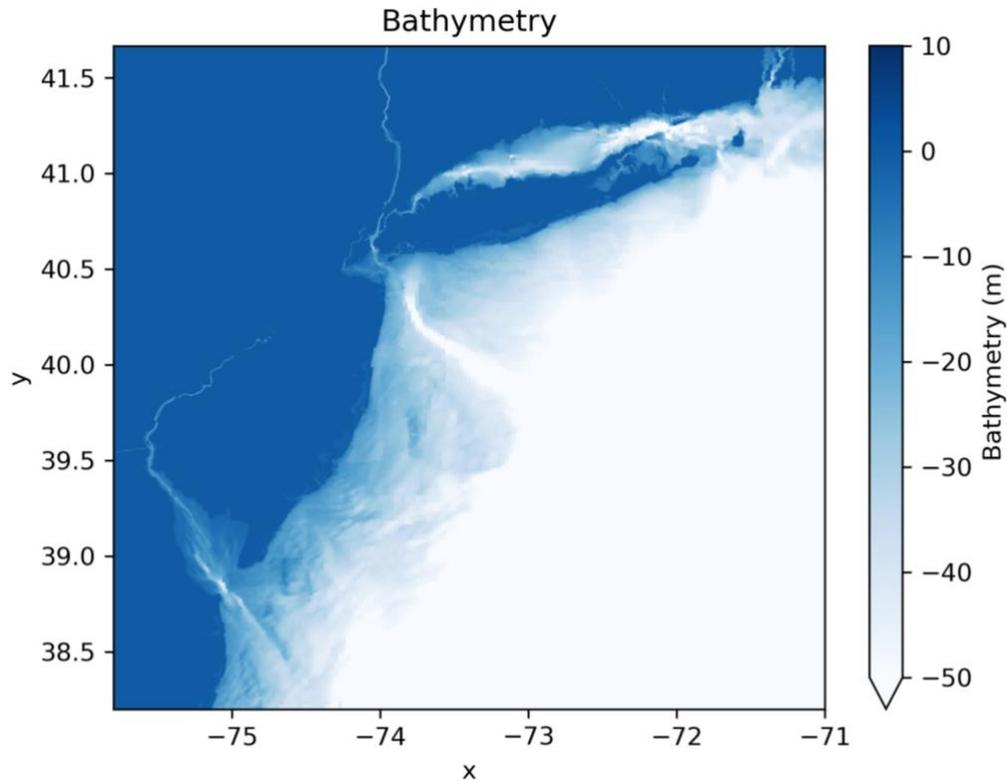
Figure 3.1 The bathymetry of the computational domain.

To achieve a balance between computational efficiency and spatial detail, an unstructured grid with a resolution up to 100 meters was employed (Fig. 3.2). This resolution is fine enough to resolve key coastal features such as inlets (e.g., Barnegat Inlet, Little Egg Inlet), estuaries, and barrier islands, which are critical for accurately simulating tidal flows and their interactions with bathymetry. The grid was designed to follow the coastline's irregular shape, with finer resolution near the shore (approximately 100 meters) and shallow regions and coarser resolution further offshore, optimizing computational resources while maintaining accuracy in dynamic coastal zones. A grid sensitivity analysis was conducted to validate this choice, comparing the 100-meter grid to a finer 50-meter grid in a sub-domain encompassing a key tidal inlet. The analysis revealed that while the finer grid provided slightly higher velocity magnitudes in the narrowest parts of the inlet, the overall patterns and energy estimates were consistent, justifying the 100-meter resolution for the broader domain to manage computational demands.
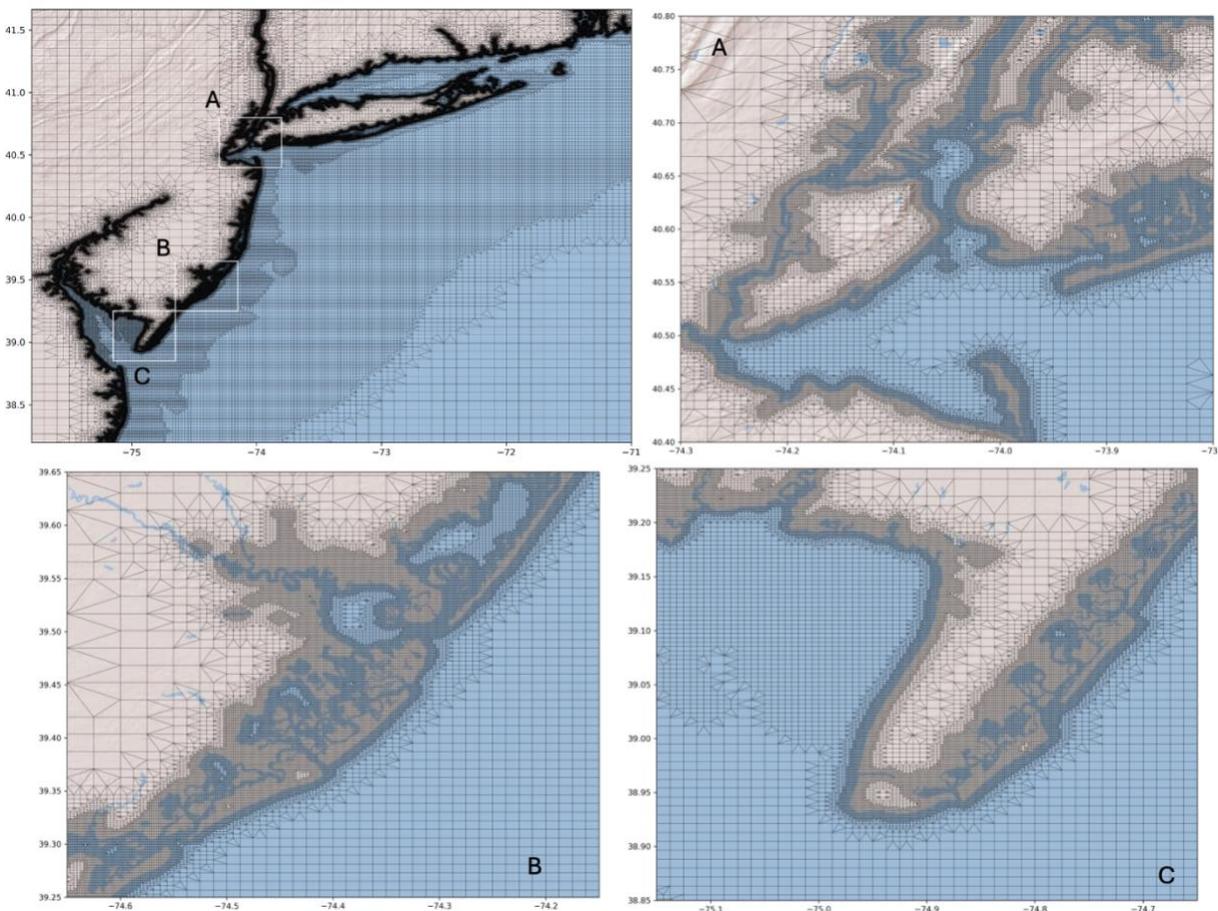
Figure 3.2 An overall and zoom-in views of the unstructured computational grid: Global grid (top left), Zone A of Hudson-Raritan Estuary (top right), Zone B around Atlantic City (bottom left), Zone C of Cape May and Delaware Bay (bottom right)

3.1.3 Boundary Condition and Parameterization

Boundary conditions were carefully defined to accurately represent the physical environment and tidal dynamics within the model domain. Open ocean boundaries were set as water level boundaries, where water levels were prescribed based on TPXO8-derived tidal harmonics (Egbert & Erofeeva, 2002). River discharges were incorporated for major freshwater inflows, such as the Delaware River and Hudson River, using real-time discharge data from the United States Geological Survey (USGS) gauging stations. These inflows were applied at upstream USGS streamgage locations of rivers, allowing the model to capture the interaction between tidal and

riverine processes, particularly in estuarine regions. Proper representation of freshwater inflows is essential in regions where river discharge can influence tidal propagation and energy availability.

Bottom friction was parameterized using Manning's formula. Manning's coefficients were set to 0.022 for the Delaware Bay and Delaware River, 0.025 for the Long Island Sound, and 0.015 for the rest of the domain, based on typical values for the respective environments. The refinements in bottom roughness parameters led to improved agreement between simulated and observed hydrodynamics, particularly in regions where seabed friction significantly influences tidal currents.

The model utilized 12 sigma layers to enhance the accuracy of surface tidal velocity predictions. This method allowed for a more detailed representation of velocity gradients within the water column, particularly in regions influenced by nonlinear flows.

3.2 Modeling results

3.2.1 Model Performance and Validation

The validation of the simulated water levels against NOAA tidal gauge observations from February 1 to March 1, 2019, demonstrates exceptional model performance across the study region (Fig. 3.3). Correlation coefficients reached 0.99 at most locations, indicating strong agreement between simulations and measurements, though slightly lower values of 0.98 were observed at sites such as the mouth of Long Island Sound and upstream estuarine or riverine areas in addition to the inland end of Long Island Sound and the Trenton station on the Delaware River. Root Mean Square Errors (RMSE) were equally impressive, remaining below 1 cm in open ocean environments and increasing modestly to around 3 cm at the inland extremities of estuaries and rivers. Skill scores are a metric commonly employed by oceanographers to assess predictive accuracy, which are defined as

$$Skill = 1 - \frac{\sum |X_{model} - X_{obs}|^2}{\sum (|X_{model} - \overline{X_{obs}}| + |X_{obs} - \overline{X_{obs}}|)^2}, \tag{3.1}$$

where the overbar indicates the average over time. The skill of this simulation ranged from 0.97 to 0.99 in open ocean settings, with a minor decline at inland sites where Trenton achieved a still

commendable 0.89. Overall, these results highlight the model's remarkable fidelity in capturing tidal dynamics, particularly in coastal and transitional zones.

Figure 3.3 Model validation: Correlation coefficient (top), RMSE (middle), Skill (bottom)

3.2.2 Spatial Distribution of Tidal Energy

The surface velocity magnitude field provides critical insights into the regions where tidal energy extraction is most feasible (Fig. 3.4). The identified high-velocity zones include the Hudson River, Cape May, Barnegat Inlet, and other tidal inlets along barrier islands, where the average surface current speed exceeds 1.5 meter per second. The relationship between velocity and power density follows a cubic trend, meaning even small increases in current speed lead to substantial gains in energy potential. The maps highlighted areas where surface currents dominate and where near-seabed velocities remain strong, allowing for a comprehensive evaluation of energy extraction opportunities at different depths.
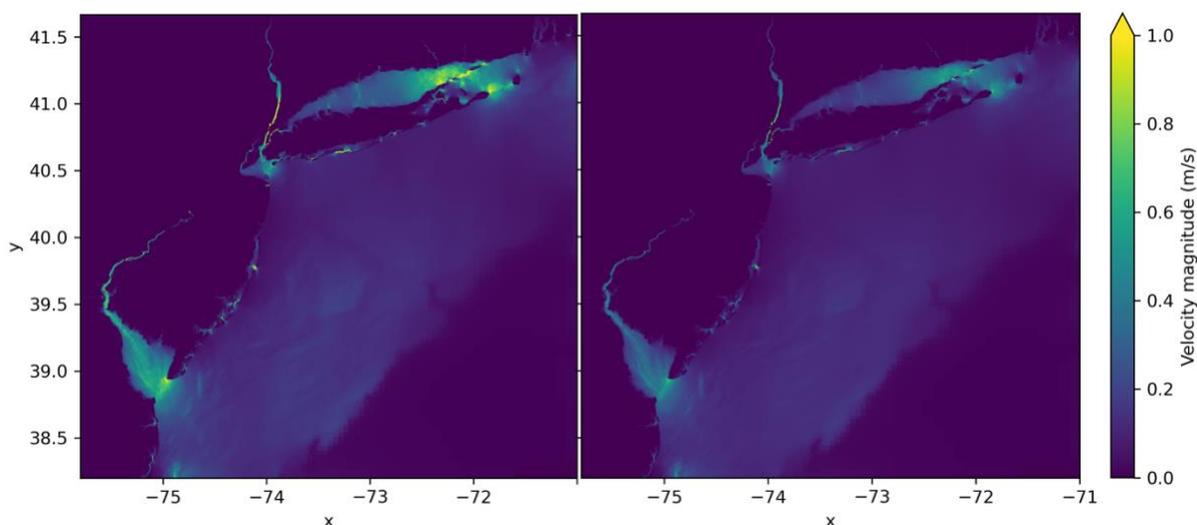
Figure 3.4 The field of mean velocity magnitude highlights the potential high velocity areas: mean velocity field in the surface layer (left) and bottom layer (right).

The power distribution maps provide a detailed assessment of tidal energy potential along the New Jersey coastline by translating tidal velocity data into power density values. These maps highlight the spatial distribution of available kinetic energy and reveal the most promising locations for energy extraction. The surface power distribution map quantifies the energy potential at the water's surface, clearly visualizing areas where tidal currents concentrate the most power. Power density is determined using the equation

$$P = \frac{1}{2}\rho V^3,$$
(3.2)

where P represents power density in watts per square meter, ρ is the density of seawater, and V is the velocity of tidal currents. Because power scales with the cube of velocity, even small increases in current speed result in significant gains in energy potential.

A time-averaged assessment of power densities refines the understanding of tidal energy potential along the coastline (Fig. 3.5). The mean surface power distribution map provides a long-term perspective. Little Egg Inlet and Barnegat Inlet maintain high power density, with an average surface power density exceeding 1000 W/m². These consistent power levels indicate the potential for reliable energy generation, indicating the practicality of tidal energy projects in these locations. The naturally intensified tidal flows in these inlets provide a predictable and stable energy resource, which is a crucial factor in the economic feasibility of renewable energy investments.

The mean bottom power distribution map further supports this long-term perspective by identifying sustained energy potential near the seabed. While bottom power densities are lower because of friction, Little Egg Inlet and Barnegat Inlet continue to show strong power levels, confirming their viability for energy harvesting. The narrow and deep nature of these channels ensures that tidal currents remain effective for power generation even at greater depths. The presence of consistent bottom power supports the strategic use of bottom-mounted turbines, particularly in areas where surface systems may face operational challenges. By maintaining a stable power supply near the seabed, these inlets provide opportunities for smaller-scale or supplementary tidal energy projects, complementing surface-based systems and contributing to a diversified energy strategy.

The distribution of tidal energy along the New Jersey coastline is shaped by its coastal morphology, with barrier islands and inlets playing a key role in concentrating tidal flows. The power distribution maps illustrate how these natural features influence both surface and bottom energy potential, guiding the placement of turbines to maximize efficiency. The sustained power densities observed in Little Egg Inlet and Barnegat Inlet confirm their suitability for tidal energy extraction, whether through surface-mounted turbines that take advantage of stronger currents at the water's

surface or bottom-mounted systems that harness energy from near-seabed flows. The findings reinforce the potential of tidal energy as a viable renewable resource for New Jersey.
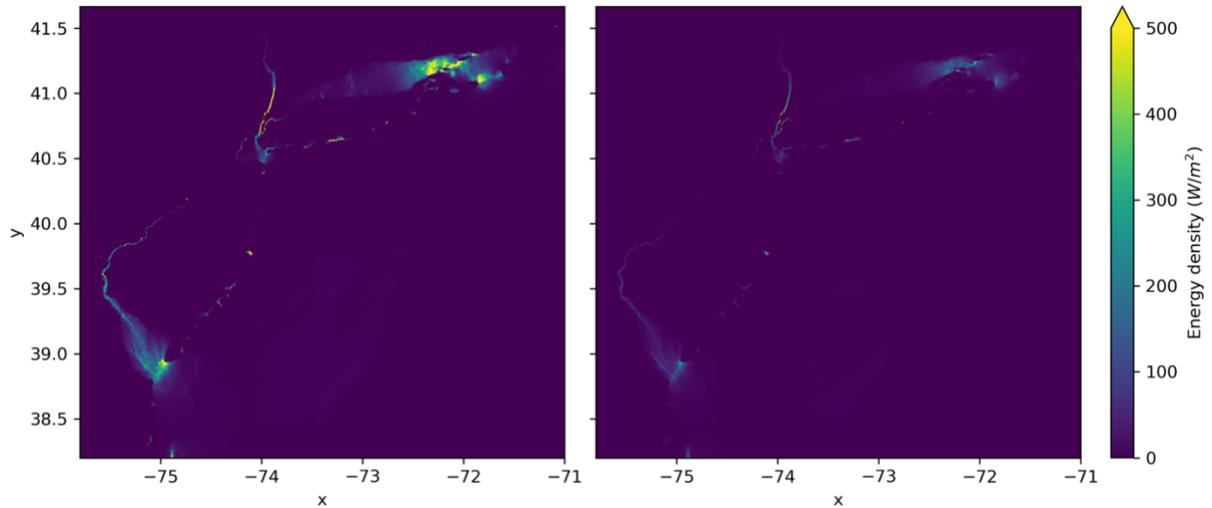

Figure 3.5 The field of mean power distribution highlights the potential high velocity areas: mean power distribution field in the surface layer (left) and bottom layer (right).

3.2.3 Theoretical Deployable Area Analysis

The simulation results delineate feasible tidal energy deployment areas across New Jersey by decomposing them into New Jersey Department of Environmental Protection (NJDEP) Watershed Management Areas (WMAs) (NJDEP Watershed Management Areas in New Jersey (Version 200901)), utilizing power density thresholds of 500 W/m², 1000 W/m², 1500 W/m², and 2000 W/m² to identify regions with varying levels of energy potential (Fig. 3.5). These thresholds reflect increasing viability for tidal turbine installations, where higher densities indicate stronger currents and greater extractable power. The areas listed in Table 3.1 are quantified in units of ×10³ m² for individual WMAs and summed to provide totals, revealing a statewide potential of approximately 11.637 km² (or 11,637 ×10³ m²) for sites exceeding 500 W/m², diminishing to 4.395 km² above 1000 W/m², 0.172 km² above 1500 W/m², and a modest 0.082 km² above 2000 W/m². This distribution underscores that while broader areas are available at lower thresholds for preliminary exploration, only select zones maintain high-intensity flows suitable for advanced deployment.

The theoretical deployment feasible areas ($\times 10^3$ m^2)			
WMA Name	> 500 (W/m^2)	> 1000 (W/m^2)	> 1500 (W/m^2)	> 2000 (W/m^2)
Hackensack, Hudson, and Pascack	3,504.10	877.61	31.25	4.029
Arthur Kill	118.33	9.41	0	0
Monmouth	59.48	2.68	1.33	0
Barnegat Bay	3,634.98	3,046.03	61.97	37.62
Mullica	164.20	79.95	46.28	30.85
Lower Delaware	65.21	0	0	0
Great Egg Harbor	276.77	35.12	7.05	0
Maurice, Salem, and Cohansey	192.74	54.25	21.42	8.57
Cape May	3,621.31	289.74	2.85	1.43
Total Area:	11,637.11	4,394.79	172.15	82.49
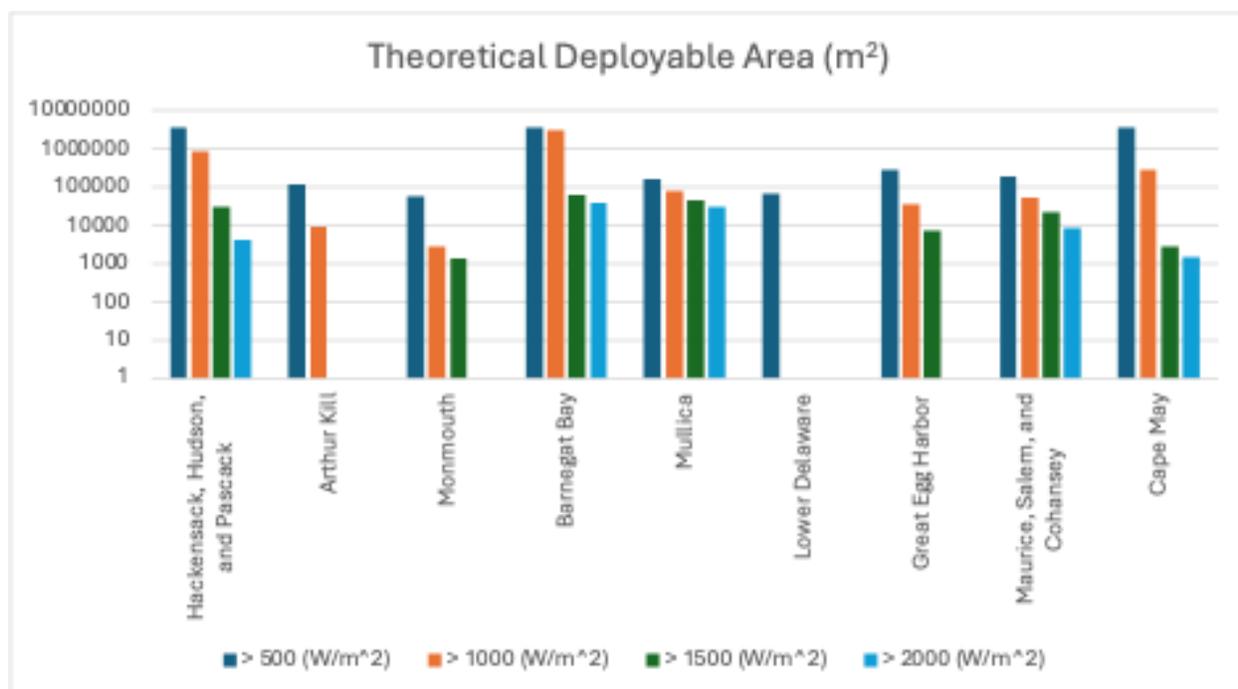
Table 3.1 The list of theoretical deployment feasible areas by WMA.

Among the WMAs, Barnegat Bay emerges as a standout region, encompassing the largest feasible areas across most thresholds: 3,635 ×10³ m² (>500 W/m²), 3,046 ×10³ m² (>1000 W/m²), 62 ×10³ m² (>1500 W/m²), and 38 ×10³ m² (>2000 W/m²), likely due to its extensive tidal inlets and barrier island configurations that channel strong currents. Similarly, Cape May ranks highly for lower thresholds with 3,621 ×10³ m² (>500 W/m²) and 290 ×10³ m² (>1000 W/m²), though its potential tapers off sharply at higher densities (3 ×10³ m² >1500 W/m² and 1 ×10³ m² >2000 W/m²), suggesting more variable flow regimes influenced by coastal geometry. The Hackensack, Hudson, and Pascack WMA also shows substantial coverage at moderate levels 3,504 ×10³ m² (>500 W/m²) and 878 ×10³ m² (>1000 W/m²) but limited high-density zones (31 ×10³ m² >1500 W/m² and 4 ×10³ m² >2000 W/m²), potentially attributable to urbanized riverine influences in the northern region.

Other WMAs contribute variably, with Mullica demonstrating notable high-density potential (164 ×10³ m² >500 W/m², escalating to 31 ×10³ m² >2000 W/m²), driven by its estuarine channels, while Maurice, Salem, and Cohansey offers balanced but smaller areas (193 ×10³ m² >500 W/m² down to 9 ×10³ m² >2000 W/m²). Regions like Great Egg Harbor (277 ×10³ m² >500 W/m²) and Arthur

Kill (118 $\times 10^3$ m² >500 W/m²) provide supplementary opportunities at lower thresholds but lack sites above 1500 W/m² or 2000 W/m², respectively. Monmouth and Lower Delaware exhibit the smallest potentials, with Monmouth at 59 $\times 10^3$ m² (>500 W/m²) and minimal higher-density areas, and Lower Delaware restricted to 65 $\times 10^3$ m² solely above 500 W/m². Overall, these results highlight a concentration of viable deployment zones in southern and central coastal WMAs, where tidal dynamics are amplified by inlets, bays, and headlands, informing targeted site selection for future tidal energy projects while emphasizing the need for environmental and infrastructural assessments in these delimited areas.
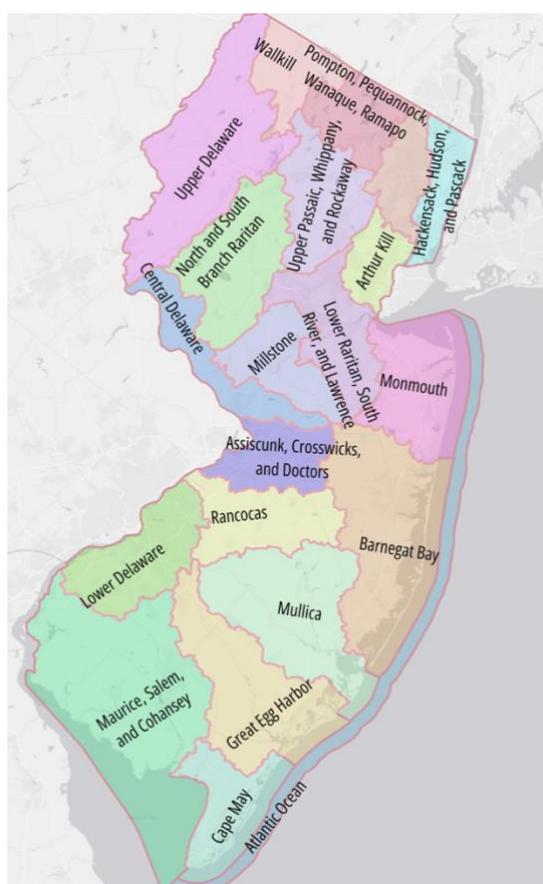

Figure 3.6 Potential tidal energy deployment areas are decomposed into NJDEP Watershed Management Areas in New Jersey (Version 200901)

While the current analysis effectively filters and quantifies feasible tidal energy deployment areas in New Jersey based on power density thresholds and watershed management zones, it notably omits considerations of ecological conflicts, such as overlaps with sensitive seagrass beds and

animal habitats that could be disrupted by turbine installations. Similarly, human activities, including shipping channels and recreational marine uses have not been factored in. These aspects will be thoroughly examined in Chapter 5 through a virtual deployment analysis, which will incorporate a broader array of marine space use conflicts, including environmental sensitivities, navigation routes, and regulatory exclusions, to refine site viability. Furthermore, this forthcoming analysis will enable the estimation of the total potential power available for harnessing, providing a more comprehensive pathway toward practical tidal energy development.

4 Wave Energy Assessment

4.1 Numerical Model Specification

4.1.1 Model Selection

The current chapter builds on the state of knowledge by implementing a calibrated SWAN model with a nested 100 m nearshore grid, extending from Maine to Florida to ensure realistic boundary conditions while resolving fine-scale transformation along New Jersey's coast. This configuration reflects the best-practice resolutions and validation strategies identified in prior literature, enabling the identification of a "wave energy corridor" with seasonal and interannual variability explicitly quantified. The resulting outputs serve as a foundation for technology matching, siting analysis, and hybrid resource integration with tidal energy potential mapped in Chapter 3.

Accurately assessing wave energy resources along the New Jersey coastline requires a robust, high-resolution numerical modeling framework capable of capturing the complex interactions between meteorological forcing, ocean dynamics, and coastal morphology. The New Jersey shoreline exhibits a highly irregular geometry, defined by a series of barrier islands, tidal inlets, and estuarine systems that dynamically interact with offshore wave fields. These features influence wave transformation processes such as refraction, shoaling, and diffraction and energy dissipation patterns due to variable bathymetry and sediment characteristics. The Simulating Waves Nearshore (SWAN) model was selected for this study to simulate these dynamics effectively. SWAN is a third-generation spectral wave model specifically developed to compute wave evolution in coastal and shallow water environments, making it ideally suited to the fine-scale topographic and hydrodynamic features along the New Jersey coast (Booij et al., 1999; Qin et al., 2005).

SWAN computes the evolution of wave fields by solving the wave action balance equation in both spectral (frequency and direction) and geographic (space and time) domains. The model operates in the action density formulation, providing an accurate framework for describing energy propagation in ambient currents and varying water depths (Delft University of Technology). This formulation is particularly advantageous in nearshore regions, where bathymetric gradients and current-induced modulations are significant. The action balance equation accounts for various

physical processes, including wind input (generation of waves from wind shear stress), nonlinear wave-wave interactions (energy transfer between wave components), whitecapping (dissipative breaking in deep water), bottom friction (interaction of waves with the seabed), and depth-induced breaking (wave breaking due to shallow water effects) (Holthuijsen et al., 1993; Van der Westhuysen et al., 2007).

In the context of the New Jersey coastline, local wind patterns, particularly nor'easters and Atlantic frontal systems, play a dominant role in generating energetic sea states during the fall and winter months. These wind events interact with offshore swell propagating from the North Atlantic, creating a mixed wave field characterized by complex frequency and directional components. The ability of SWAN to resolve such spectral variability is crucial for estimating wave power potential and assessing the suitability of various wave energy converter (WEC) technologies, each operating optimally within specific wave frequency bands (Zijlema, 2010).

Furthermore, SWAN's numerical scheme allows for the incorporation of unstructured or curvilinear grids, enabling detailed resolution of coastal features without compromising computational efficiency. This is especially important when modeling the barrier island systems along New Jersey, where narrow inlets and rapidly changing bathymetry influence wave transformation and dissipation. By employing nested grids with higher resolution in targeted subdomains, such as near Barnegat Bay or Little Egg Inlet, the model can capture localized wave energy hotspots that may otherwise be missed in coarser simulations (Qin et al., 2005; Dietrich et al., 2011).

To simulate wave dynamics along the New Jersey coastline, the SWAN model was employed, leveraging its ability to solve the wave action balance equation, which governs the evolution of wave action density over time, space, frequency, and direction. This equation, central to SWAN's capability to model wave propagation and transformation, is expressed as:

$$\frac{\partial \widehat{N}}{\partial t} + \frac{\partial}{\partial \phi}\left(\partial_\phi \widehat{N}\right) + \frac{\partial}{\partial \lambda} + \left(\partial_\lambda \widehat{N}\right) + \frac{\partial}{\partial \sigma}\left(\partial_\sigma \widehat{N}\right) + \frac{\partial}{\partial \theta}\left(\partial_\theta \widehat{N}\right) = \frac{S_{tot}}{\partial} \qquad (4.1)$$

where, $\widehat{N}$ it represents the wave action density adjusted for spherical coordinates ϕ and λ denotes latitude and longitude, σ is the relative wave frequency, and θ is the wave direction. The terms c_ϕ,

c_λ, c_σ, and c_θ are the propagation velocities in their respective dimensions while S_{tot} encapsulating key physical processes such as wind-driven wave growth, nonlinear energy transfers, and dissipation from whitecapping, bottom friction, and depth-induced breaking. This formulation, tailored for the large-scale domain of the US East Coast, ensures SWAN accurately captures wave dynamics across both nearshore and offshore regions, making it an ideal tool for high-resolution wave energy assessments in this study.

4.1.2 Computational Domain and Grid

The computational grid for the SWAN model was developed to simulate wave dynamics across a broad section of the U.S. East Coast while ensuring high-resolution fidelity near the New Jersey coastline. The full model domain extends from Maine to Florida and reaches offshore to the mid-Atlantic Ridge, capturing large-scale wave systems and swell propagating toward the mid-Atlantic region. This extensive coverage was necessary to ensure realistic offshore boundary conditions for wave energy assessments near New Jersey.

To balance computational efficiency and spatial resolution, a dual-resolution grid structure was implemented. The outer domain used a coarse 1-kilometer resolution mesh to simulate long-range wave propagation and offshore interactions. In contrast, a refined 100-meter resolution grid was applied to nearshore areas along the New Jersey coast, where a detailed representation of wave transformation processes is essential for accurate energy evaluation. This fine-scale mesh allowed the model to resolve wave shoaling, refraction, depth-induced breaking, and bottom friction more precisely, which are critical for determining localized wave energy potential. The refined sub-domains were concentrated along the central-eastern shoreline of New Jersey; a region identified in the BPU analysis as having high wave energy potential. These high-resolution areas included complex coastal features such as tidal inlets, barrier island systems, and nearshore shoals. Grid design was coordinated with proposed infrastructure elements, including export cable routes, to support realistic feasibility assessments.

Sensitivity analyses demonstrated that the 100-meter resolution grid effectively captured key wave transformation dynamics without incurring excessive computational cost. This resolution was

found to be an optimal balance, providing sufficient spatial detail for accurate simulation of nearshore energy hotspots while maintaining manageable run times for multi-month simulations.

When combined with calibrated ERA5 wind forcing and high-resolution bathymetric inputs, the resulting grid configuration ensured that wave energy spatial variability was accurately represented. As part of the state's broader renewable energy planning objectives, this modeling framework laid the foundation for identifying, evaluating, and ranking promising locations for wave energy capture along the New Jersey coast.

4.1.3 Boundary Condition and Parameterization

Accurate wave modeling along the New Jersey coastline required high-quality bathymetric data and calibrated wind forcing to drive the SWAN simulations. Bathymetry plays a critical role in modulating wave transformation processes such as shoaling, refraction, and breaking. To capture the complex underwater topography near the coast, high-resolution bathymetric data were obtained from NOAA's Coastal Relief Model, which provides a spatial resolution of approximately 90 meters. These data accurately represented coastal features such as barrier islands, tidal inlets, and submerged shoals that significantly influence wave behavior in the nearshore zone. For the offshore portions of the domain, NOAA's ETOPO1 Global Relief Model was used, offering a coarser resolution of approximately 1800 meters. While this lower resolution is insufficient for resolving small-scale topographic variability, it is adequate for representing deep-water bathymetry where wave transformation is less sensitive to fine-scale bottom features. The coastal and offshore datasets were interpolated onto the SWAN computational grid using bilinear interpolation techniques, ensuring smooth transitions across nested domains and preserving bathymetric gradients essential to wave energy assessments.

Wind forcing was the model's sole meteorological input to drive wave generation. ERA5 Hourly Reanalysis wind data, produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Hersbach et al., 2020), were employed at a spatial resolution of approximately 32 kilometers. However, initial simulations using uncalibrated ERA5 data resulted in consistent underestimation of significant wave heights, particularly during energetic events. This discrepancy was attributed to the known tendency of ERA5 to underestimate peak wind speeds in coastal and

storm-prone regions. To address this limitation, the ERA5 wind data were calibrated against local wind observations, including those from NOAA buoys situated along the New Jersey coast. This recalibration process significantly improved the model's ability to reproduce observed wave conditions, particularly at high-energy sites such as Barnegat Inlet. The use of calibrated wind forcing enhanced the accuracy of wave energy estimates, supporting the study's goal of providing a reliable spatial assessment of wave power density along the New Jersey shoreline.

4.2 Results

4.2.1 Model Performance and Validation

The SWAN hindcast was validated against in-situ measurements from NOAA's Barnegat buoy. Early simulations driven by uncalibrated ERA5 winds underestimated peak significant wave heights during winter storm events. To correct this, ERA5 winds were bias-adjusted to local observations, which substantially improved the model's ability to reproduce observed wave characteristics.

Validation focused on January 1–14, 2022. Time-series comparisons of wave energy and significant wave height demonstrate that the calibrated model tracks the timing and magnitude of events: the energy metric aligns with buoy estimates (Fig. 4.1), and the significant wave height series shows close agreement across calm-to-storm conditions (Fig. 4.2). Together, these results confirm that the wind calibration addressed the underestimation bias and increased the reliability of modeled wave dynamics along the New Jersey coastline.

Quantitatively, time-matched pairs of modeled and observed significant wave height yield a Pearson correlation R = 0.87 (87%) and RMSE = 0.85 m over the validation period. Scatter increases at higher sea states, but overall skill indicates faithful reproduction of observed H_s and supports the use of the calibrated fields for subsequent resource mapping and analysis (Fig. 4.3).
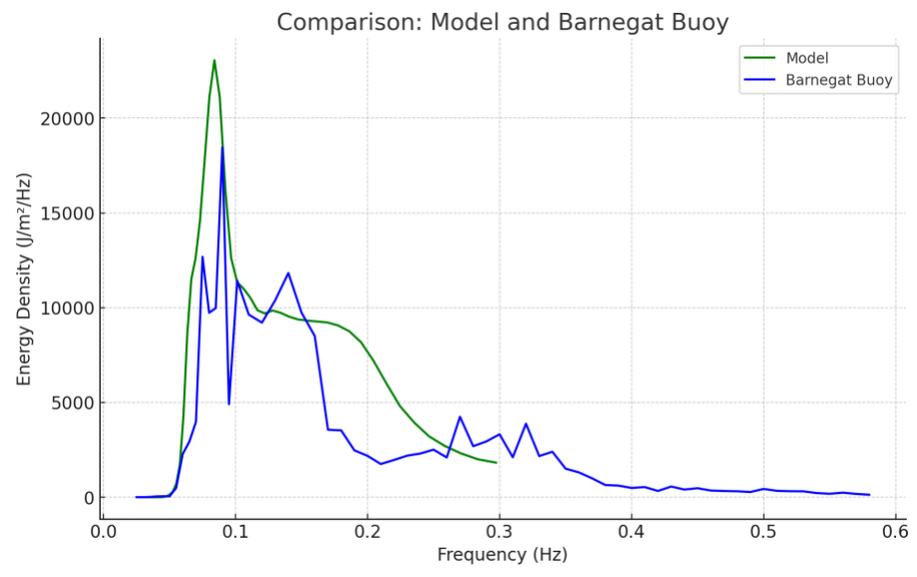
Figure 4.1 The modeled wave energy results are compared with buoy observations at NOAA's Barnegat Buoy station from January 1 to January 14, 2022, demonstrating the agreement between the simulation and the measured data.
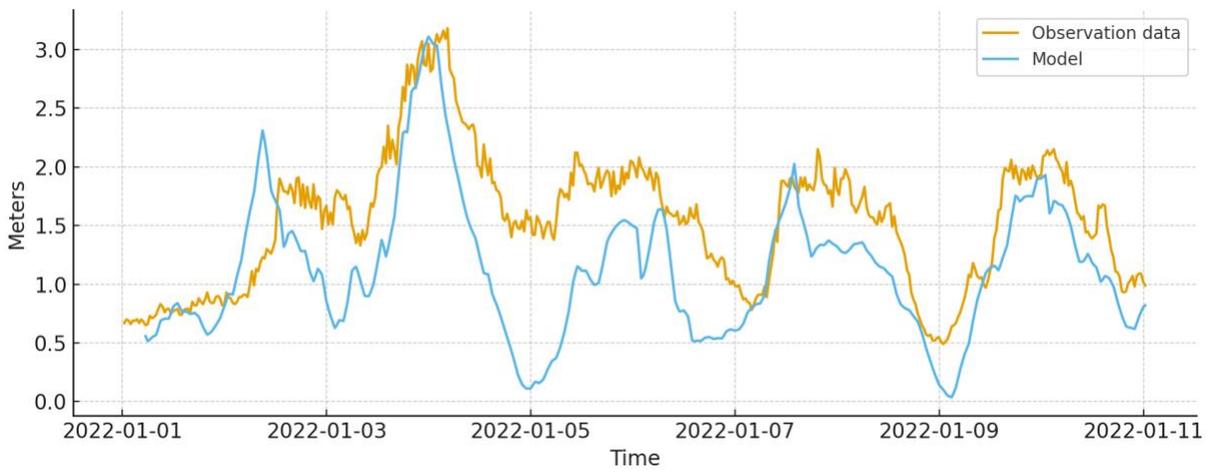

Figure 4.2 The modeled significant wave heights are compared with buoy observations at NOAA's Barnegat Buoy station from January 1 to January 14, 2022, demonstrating the model's accuracy in reproducing observed wave conditions.
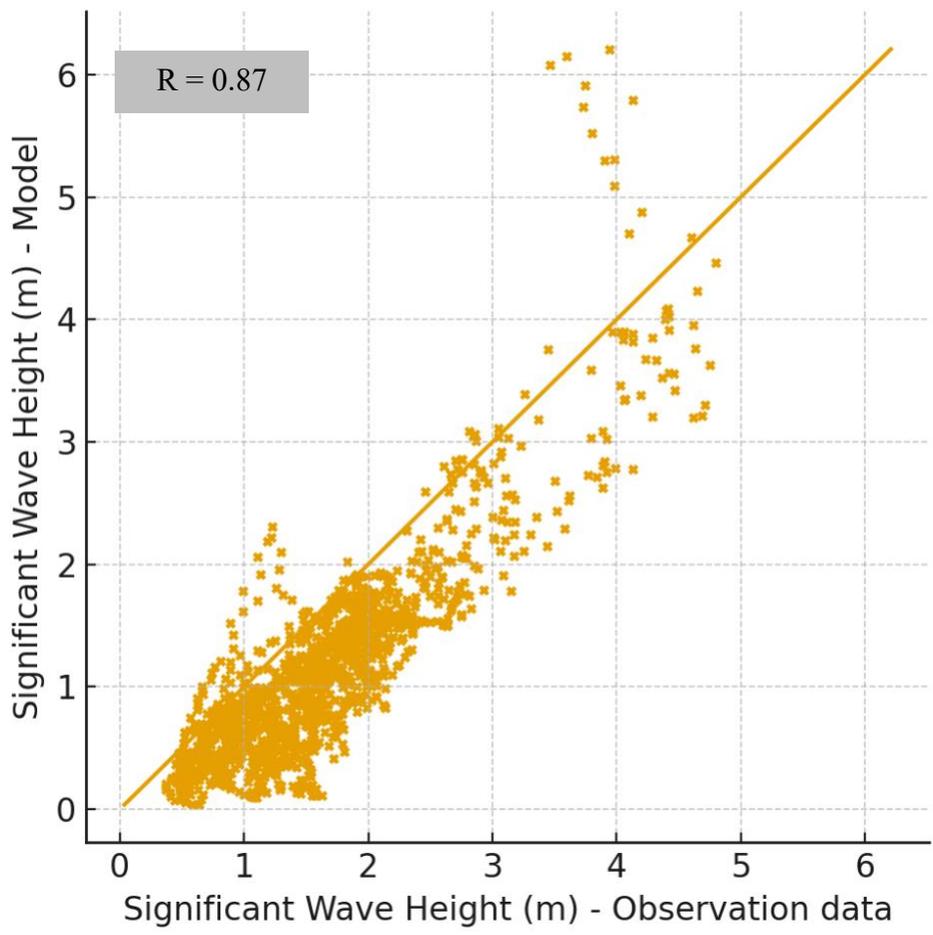
Figure 4.3 Scatter of modeled significant wave height versus buoy observations (m) for the validation period along the New Jersey shelf; each point is a time-matched pair, and the solid line is the 1:1 reference, indicating good agreement across typical seas with greater spread at higher wave heights.

4.2.2 Spatial Distribution of Wave Energy

The calibrated SWAN model simulated wave power density for the full calendar year of 2022. The annual median power density map (Fig 4.4) reveals a clear spatial pattern, with the highest energy concentrations occurring along the central-eastern shelf of New Jersey. These zones are typically situated offshore of barrier islands where bathymetric gradients and fetch exposure strongly influence wave shoaling.
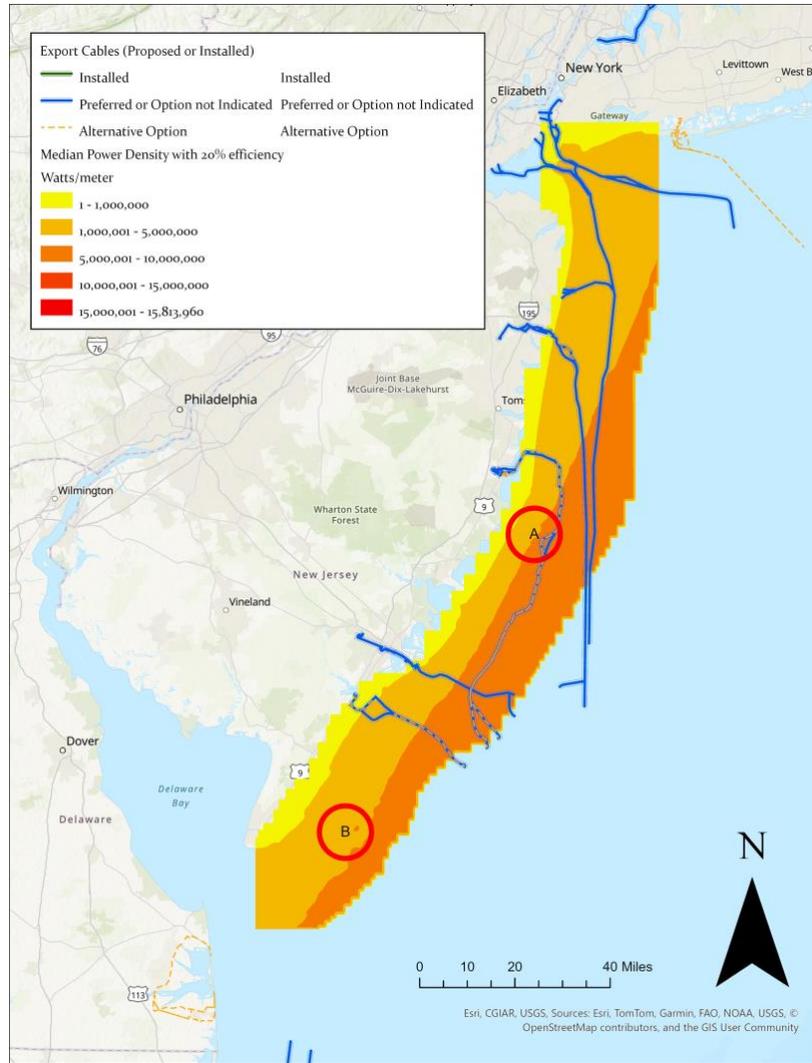
Figure 4.4 The median wave power density along the New Jersey coastline, highlighting high-energy areas (A and B) and existing export cable routes.

The wave power density was calculated using the standard deep-water wave energy flux equation:

$$P = \frac{\rho g^2}{64\pi} H_s T_e \tag{4.2}$$

where ρ water density g is, gravitational acceleration is, H_s is the significant wave height, and T_e is the energy period.

4.2.3 Temporal Variability

Seasonal analysis of wave power revealed distinct variability across the year. Energy levels were highest in the winter months (December through February), corresponding to the increased frequency and intensity of extra-tropical storms along the Mid-Atlantic coast. In contrast, summer months exhibited lower wave energy levels, with median values dropping below 5 kW/m across most domains.

Fig.4.4 presents a monthly breakdown of wave power density averaged over the high-energy region. The pronounced seasonality observed here highlights the importance of considering temporal intermittency in any potential wave energy harvesting strategy. While winter conditions offer favorable energy yields, summer intermittency may require integration with complementary renewable sources or energy storage systems.
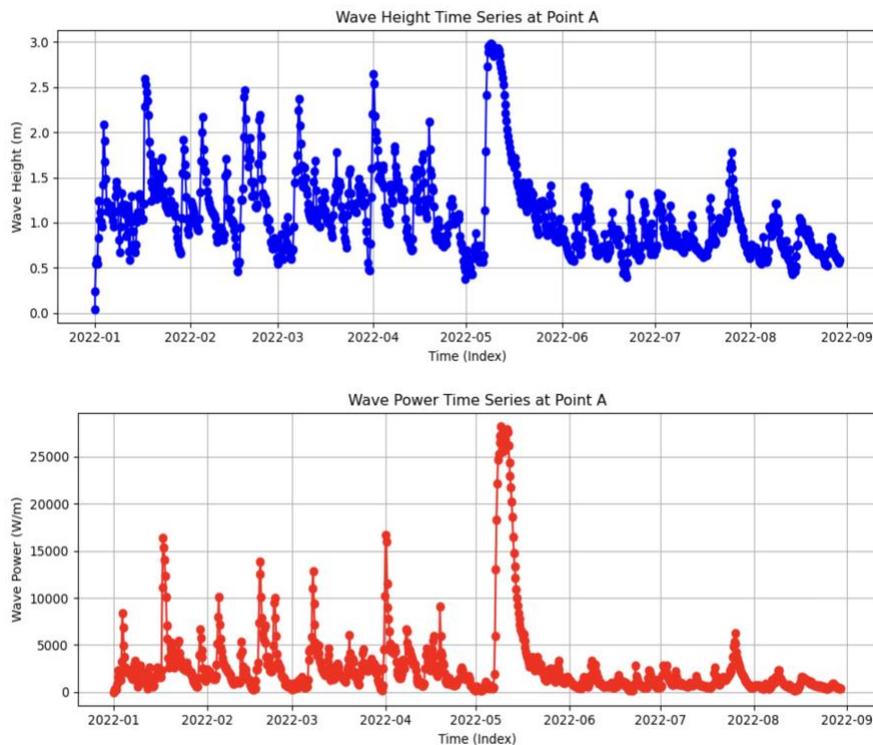

Figure 4.5 shows the time series of wave height (top) and wave power (bottom) at Point A for 2022, illustrating seasonal variability and peak storm events.
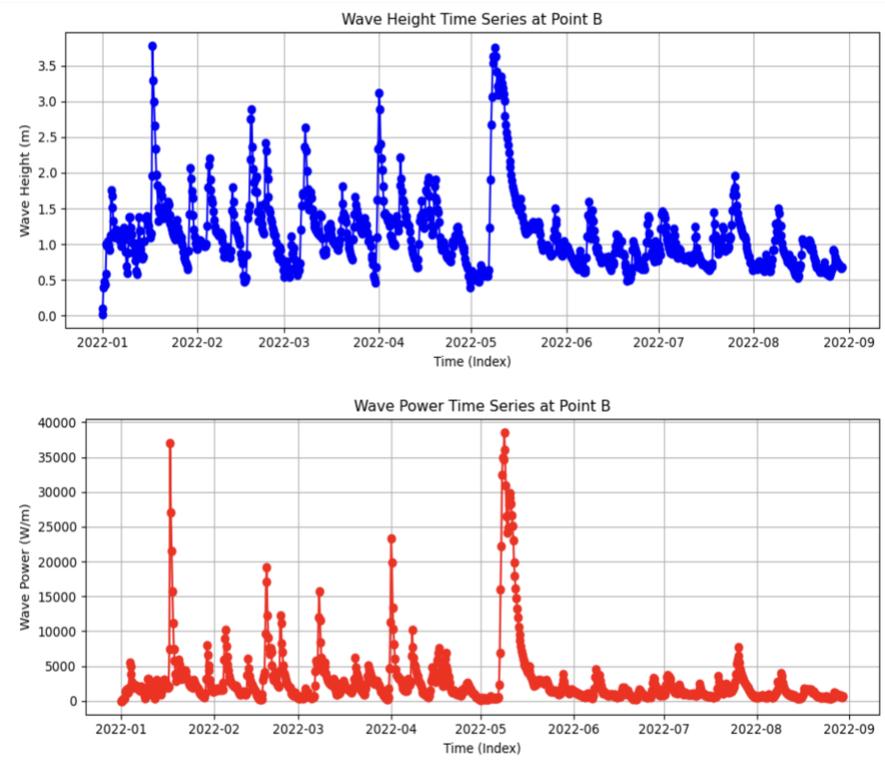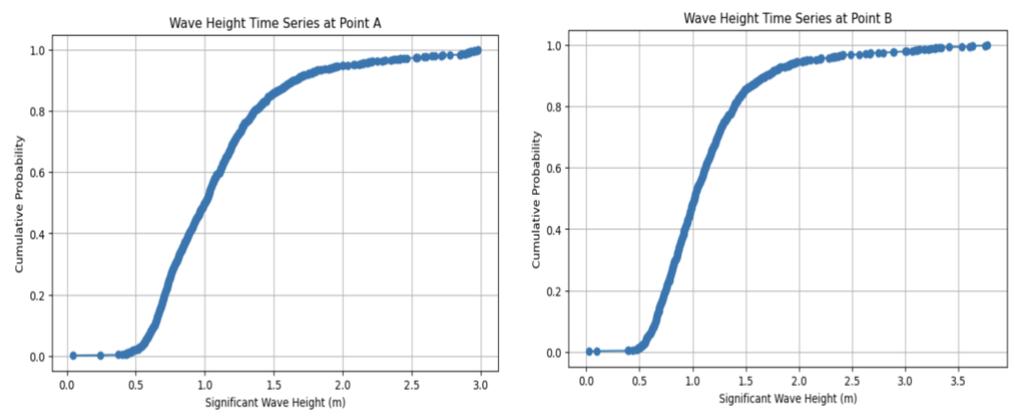
Figure 4.6 shows the time series of wave height (top) and wave power (bottom) at Point B for 2022, highlighting periods of high energy during storm events.
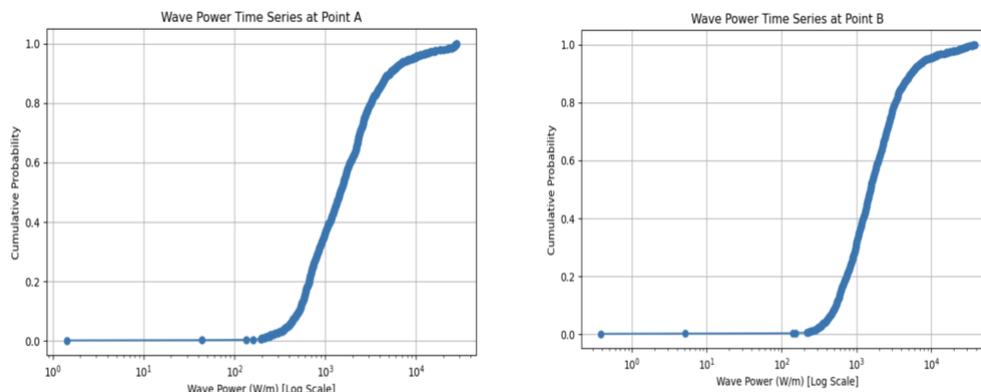
Figure 4.7 shows the cumulative probability distributions of significant wave height (top) and wave power (bottom) at Points A (left) and B (right) for 2022, illustrating the frequency and variability of wave conditions and energy potential throughout the year.

4.2.4 Seasonal–Regional Wave Composites for New Jersey

To contextualize and cross-check the hindcast results presented above, this study incorporates curated seasonal wave-map panels prepared for the New Jersey coast. The Figs presented here summarize nearshore conditions for Winter (January–March) and Spring (April–June) across three subregions, North, Central, and South, and are used here as regional evidence to compare against our SWAN-based estimates on the 100-m nearshore mesh (Fig 4.7–4.9). While our quantitative metrics (e.g., significant wave height distributions and wave power flux) are computed directly from the calibrated SWAN simulations, providing a synoptic view of spatial patterns during distinct seasonal regimes and therefore serving as an external, map-based check on the patterns resolved by the model.

The winter composites (Fig 4.7–4.9, left panels) consistently indicate enhanced exposure of the open coast to energetic North Atlantic storm conditions, with stronger gradients near headlands and alongshore variability associated with bathymetric controls and shoreline orientation. These features correspond to the elevated wintertime wave power corridors identified in 4.2.2–4.2.3 and help explain the observed concentration of higher fluxes along segments of the central shelf. By contrast, the spring composites (right panels) depict a moderated wave climate with reduced event

intensity and shorter peak-period conditions, aligning with the seasonal reduction in power flux and narrower exceedance ranges reported in our monthly statistics.

Beyond validation, the regional breakdown is directly useful for technology matching and early-stage sitting. In winter-dominant reaches (particularly along the central subregion), point-absorber and oscillating water column devices would benefit from robust storm survivability envelopes and maintenance strategies that avoid peak storm windows, whereas attenuator-type concepts may capitalize on the more regular, lower-energy spring regime for O&M access. The north–south contrast also underscores the need to treat the New Jersey coast as a suite of subregions rather than a single homogeneous resource: differences in exposure, shoreline geometry, and nearshore bathymetry translate into distinct spectra and directional spreading that should be reflected in device tuning, array spacing, and cable routing.

In summary, the seasonal analysis and our high-resolution SWAN outputs are mutually consistent: both indicate a winter-intensified resource with clear alongshore structure and a comparatively subdued spring regime.

Figure 4.8 The high-resolution wave model results for the northern New Jersey coast, with winter conditions (January–March) on the left and spring conditions (April–June) on the right, along with the corresponding time series of wave power (W/m) variability for the same period.

Figure 4.9 The high-resolution wave model results for the central New Jersey coast, with winter conditions (January–March) on the left and spring conditions (April–June) on the right, illustrating seasonal changes in wave energy distribution.
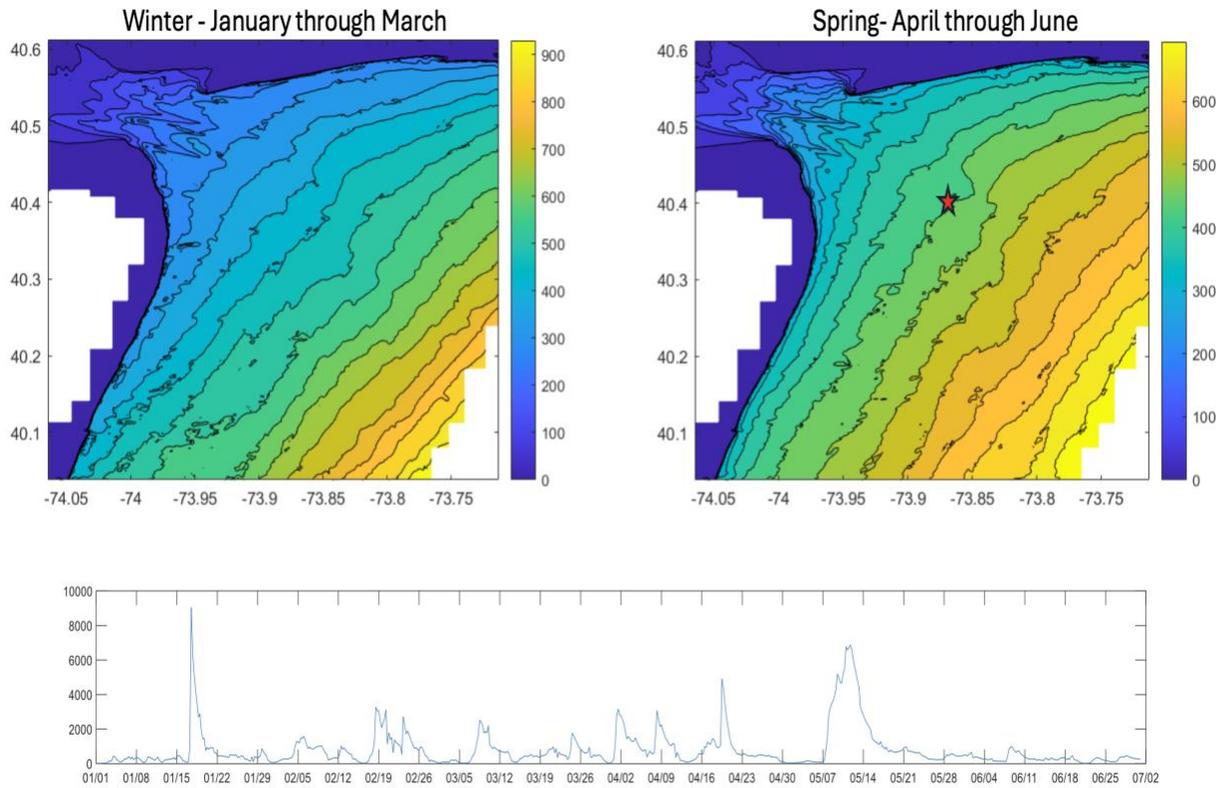
Figure 4.10 The high-resolution wave model results for the southern New Jersey coast, with winter conditions (January–March) on the left and spring conditions (April–June) on the right, along with the corresponding time series of wave power variability for the same period.
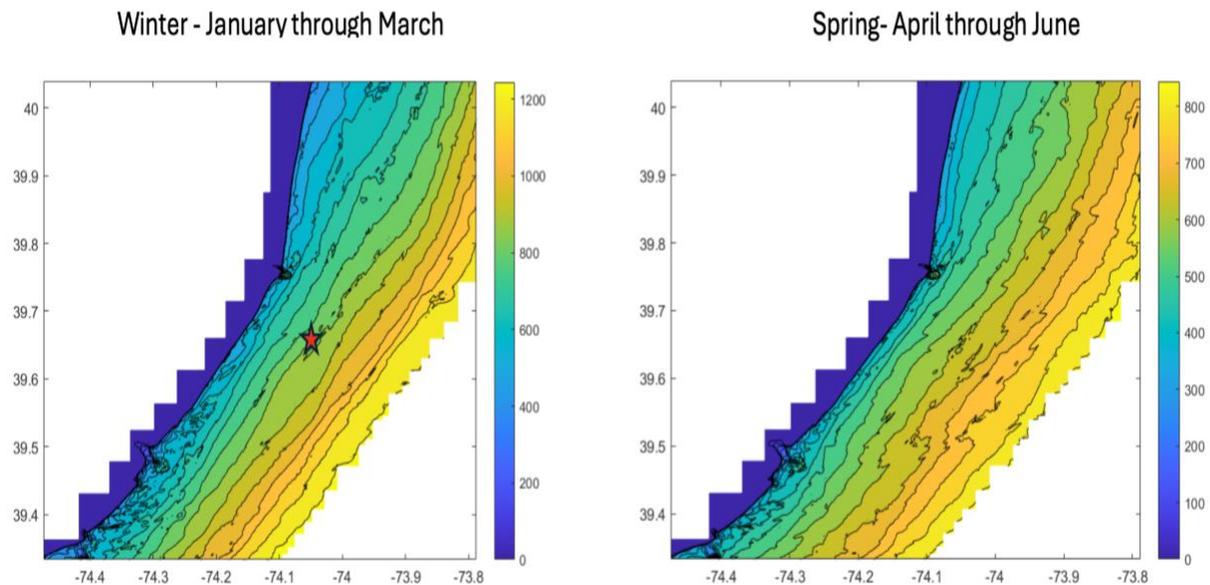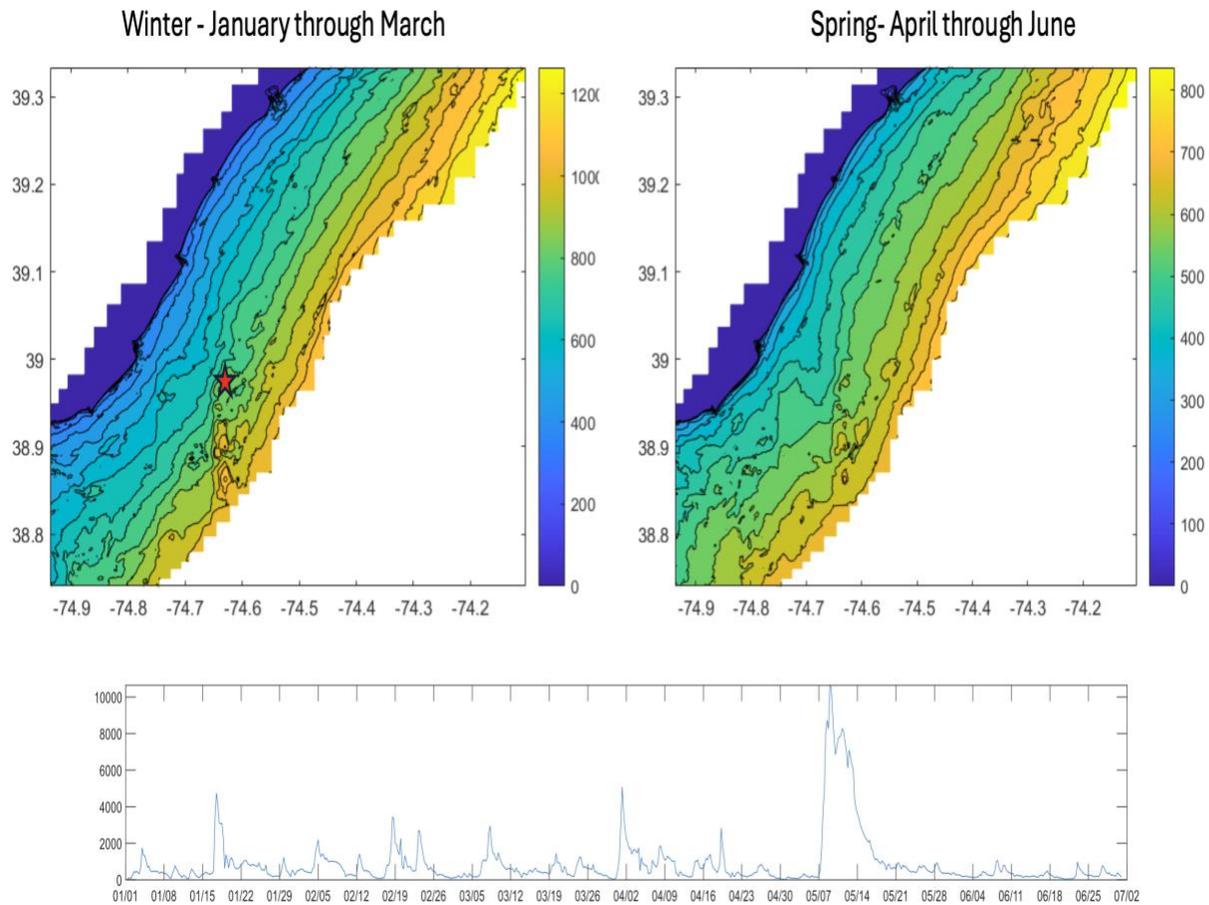
5 Regulatory Framework and Permitting Considerations for Tidal and Wave Energy in New Jersey

5.1 Introduction

Marine renewable energy (MRE) projects, including tidal and wave energy systems, represent a promising pathway to sustainable power generation along New Jersey's coastline. However, their development must navigate a multifaceted regulatory landscape to ensure compliance with environmental protections, safety standards, and socioeconomic considerations. This chapter synthesizes key findings from a review of federal and state regulations relevant to MRE, with a focus on operational noise, electromagnetic fields (EMF), involved agencies, and licensing requirements. By addressing these elements, we highlight potential barriers and opportunities for feasibility in New Jersey, where tidal hotspots (e.g., Barnegat Inlet and Cape May) and wave energy corridors (e.g., central-eastern shelf) have been identified in prior chapters. Understanding these regulations is essential for site-specific evaluations, as they influence project siting, design, and mitigation strategies to minimize impacts on marine ecosystems, navigation, and cultural resources. This analysis extends our resource characterization by incorporating regulatory constraints, ensuring that recommended sites are not only energetically viable but also permittable.

5.2 Animal Collision Risk

Regulations concerning animal collision with tidal and wave energy devices in the United States are managed through a risk-based approach rather than strict numerical standards. There are no federal or state regulations that set a specific number of acceptable animal fatalities. Instead, the focus is on a comprehensive, project-specific assessment and the implementation of avoidance, minimization, and monitoring protocols.

Federal Regulations

The primary federal statutes governing animal collisions are the **Marine Mammal Protection Act (MMPA)** (Marine Mammal Protection Act of 1972) and the **Endangered Species Act (ESA)** (Endangered Species Act, 1973). These acts prohibit the "take," including killing or injuring, of

marine mammals and threatened or endangered species (NOAA Fisheries, 2025). While the most significant collision risk for marine mammals and sea turtles in the context of offshore energy comes from vessel strikes during construction and maintenance, tidal and wave energy devices themselves also pose a potential collision risk (Tethys, 2020c).

The Bureau of Ocean Energy Management (BOEM), which oversees offshore energy leasing, requires developers to submit detailed Construction and Operations Plans (COPs) that include a thorough analysis of collision risks (BOEM, 2020). These plans must outline how the project will be designed and operated to prevent "undue harm or damage to... natural resources" (U.S. Geological Survey, 2024). In consultation with NOAA Fisheries, developers are required to propose mitigation measures. These often include:

- Strategic siting: Avoiding known migration routes or areas of high animal density.
- Pre- and post-construction monitoring: Using visual and acoustic surveys to establish baseline animal behavior and to detect any changes or fatalities after the devices are installed.
- Operational adjustments: In some cases, regulations may require the ability to slow or shut down turbines if a protected species is detected in the area (U.S. Geological Survey, 2024).

The focus is on a precautionary approach, given the limited empirical data on collision rates with these technologies (Tethys, 2020).

New Jersey State Regulations

New Jersey's state-level regulations complement the federal framework, primarily governing projects in state waters (generally within 3 nautical miles of the coast) and the onshore portions of projects. The New Jersey Department of Environmental Protection (NJDEP), through the Coastal Area Facility Review Act (CAFRA) and other coastal rules, requires a detailed environmental assessment for coastal development (New Jersey Department of Environmental Protection, n.d.b).

For offshore energy projects, the NJDEP's review process includes evaluating potential impacts on birds, bats, and other marine organisms. While the regulations for marine turbines are still evolving, the state's technical manual for wind turbines on land provides an insight into its

regulatory philosophy (New Jersey Department of Environmental Protection, 2010). For example, the manual requires pre- and post-construction monitoring for birds and bats, with the scope of monitoring dependent on the size of the turbines (New Jersey Department of Environmental Protection, 2010). While this is not specific to underwater devices, the principles of pre- and post-construction monitoring and the focus on protected species are applicable to tidal and wave energy. The state's Research and Monitoring Initiative (RMI) further addresses this by funding studies to fill knowledge gaps about how these technologies impact marine life, including potential collision risks (New Jersey Department of Environmental Protection, n.d.d).

5.3 Flooding and Shoreline Erosion Risk

Federal Regulations

At the federal level, there are no specific regulations for tidal and wave energy that directly address flooding risk or shoreline erosion as a primary purpose. However, the regulatory framework for offshore and coastal projects requires a comprehensive assessment of these risks through environmental impact statements. The U.S. Army Corps of Engineers (USACE), in particular, plays a critical role in regulating coastal development and is the lead agency for federal shore protection projects (U.S. Army Corps of Engineers, n.d.b). Tidal and wave energy devices, especially those that are fixed or part of shoreline infrastructure, would fall under the USACE's jurisdiction under Section 10 of the Rivers and Harbors Act or Section 404 of the Clean Water Act, which require permits for any structures in navigable waters or for the discharge of dredged or fill material (U.S. Army Corps of Engineers, n.d.a). These permits would require developers to demonstrate that their projects will not cause "unreasonable" flooding or erosion. The USACE's general policy is to protect and manage shorelines to ensure public access and environmental safeguards (U.S. Army Corps of Engineers, n.d.c).

New Jersey State Regulations

New Jersey's regulatory approach is more explicit and stringent due to the state's significant coastal vulnerability. The NJDEP regulates coastal development through the Coastal Area Facility Review Act (CAFRA) and the Coastal Zone Management Rules (N.J.A.C. 7:7) (New Jersey State Policy

Lab, 2024). These regulations are designed to protect coastal resources and guide development in a manner that minimizes environmental harm. For projects in state waters or those that affect the shoreline, developers must demonstrate that their project will not "cause or contribute to" flooding or erosion (New Jersey State Policy Lab, 2024).

The NJDEP has been a leader in addressing climate-related risks through its Resilient Environments and Landscapes (REAL) initiative. As part of this, the state has updated its coastal flood rules to account for sea-level rise. A key amendment, for example, now requires developers to use a Climate-Adjusted Flood Elevation (CAFE) for new construction. This elevation is based on adding a factor of 4 feet to the Federal Emergency Management Agency's (FEMA) 100-year flood elevation in tidal areas (CSG Law, 2025). The NJDEP also promotes the use of "living shorelines," which involve using natural materials to manage erosion and protect coastal habitats, as an alternative to traditional hardened structures (Cornell Law School, 2025). While these regulations are not specific to tidal or wave energy, any project of this nature would have to meet these stringent coastal protection standards, particularly if it is a nearshore or shoreline-integrated device.

5.4 Operational Noise Regulations

Federal Regulations

At the federal level, the **Marine Mammal Protection Act (MMPA)** (Marine Mammal Protection Act of 1972) and the **Endangered Species Act (ESA)** (Endangered Species Act, 1973) are the primary drivers of regulations concerning underwater noise. The MMPA prohibits the "take" of marine mammals, which includes harassment from noise. The National Oceanic and Atmospheric Administration (NOAA) Fisheries and the Bureau of Ocean Energy Management (BOEM) are the lead federal agencies responsible for regulating offshore energy projects, including assessing and mitigating noise impacts.

To comply with the MMPA, developers must obtain an incidental take authorization from NOAA Fisheries if their activities are expected to harm or harass marine mammals. These authorizations, such as the "Incidental Take Regulations for the Ocean Wind 1 Project, Offshore New Jersey,"

include mandatory mitigation and monitoring measures (NOAA Fisheries, 2023). For example, developers are required to use "protected species observers" and "passive acoustic monitoring" during noisy activities like pile-driving to ensure that marine mammals are not in a designated "exclusion zone" (NOAA Fisheries, n.d.). The majority of takes authorized for offshore wind activities are for "Level B harassment," which is a disruption of behavioral patterns or a temporary reduction in hearing sensitivity, not serious injury or death (NOAA Fisheries, n.d.).

New Jersey State Regulations

While federal agencies regulate activities in federal waters (generally more than 3 nautical miles offshore), the **New Jersey Department of Environmental Protection (NJDEP)** has regulatory authority over projects in state waters, including the review of cables and onshore infrastructure. The NJDEP's **Coastal Zone Management Rules (N.J.A.C. 7:7)** and the **Coastal Area Facility Review Act (CAFRA)** permit process are the primary mechanisms for this oversight (New Jersey Department of Environmental Protection, n.d.b). These regulations are part of New Jersey's federally approved Coastal Management Program under the **Coastal Zone Management Act (CZMA)**, which allows the state to ensure federal projects are consistent with its coastal policies (New Jersey Department of Environmental Protection, n.d.b).

For noise specifically, New Jersey's regulations for marine energy projects are more focused on the general impacts on marine ecosystems rather than specific decibel limits. However, the state has broader regulations on vessel noise. Under the **Boating Regulations (N.J. Admin. Code § 13:82-4.2)**, no person may operate a vessel capable of emitting noise in excess of 90 dB in New Jersey waters (New Jersey Administrative Code, 2023). While this does not directly apply to a stationary tidal or wave energy device, it highlights the state's existing framework for managing waterborne sound. Additionally, New Jersey has established a **Research and Monitoring Initiative (RMI)** to scientifically study the impacts of offshore wind, which includes a focus on passive acoustic monitoring for whales and other marine life (New Jersey Department of Environmental Protection, n.d.d).

5.5 Electromagnetic Fields (EMF) Regulations

Federal and New Jersey state regulations on electromagnetic fields (EMF) from tidal and wave energy devices are not as explicit as those for underwater noise. Rather than setting specific numerical limits for EMF, the regulatory approach is embedded within broader environmental review processes, focusing on research, mitigation, and environmental impact assessments.

Federal Regulations

At the federal level, there are no specific, overarching standards limiting EMF from power lines or similar sources (U.S. Environmental Protection Agency, n.d.). This is because the regulatory authority is distributed among various agencies, and the focus is on the potential impacts of EMF on specific protected species rather than on human health or general environmental standards (BOEM, n.d.b). The BOEM as the lead federal agency for offshore energy, requires developers to conduct comprehensive environmental reviews, including assessments of potential EMF impacts, as part of their Construction and Operations Plans (BOEM, n.d.c).

The **MMPA** and **Endangered Species Act (ESA)** are central to this process. While these acts primarily address physical and acoustic disturbances, their purview extends to any potential harm to protected species. Since some marine animals, such as sharks, rays, and certain fish, use the Earth's magnetic fields for navigation, predator detection, and prey location, the EMF emitted from submerged cables is a point of concern (New Jersey Department of Environmental Protection, n.d.a). BOEM works in consultation with NOAA Fisheries to ensure these potential impacts are considered and that developers propose mitigation measures, such as burying cables to a depth of 5 to 6.6 feet (1.5 to 2 meters), to reduce EMF exposure to marine life (BOEM, n.d.a).

New Jersey State Regulations

New Jersey's regulatory framework mirrors the federal approach by integrating EMF considerations into its environmental permitting process. The NJDEP has regulatory authority over projects in state waters and for the onshore portions of projects, particularly through the **Coastal Area Facility Review Act (CAFRA)** permit and the **Coastal Zone Management Rules (N.J.A.C. 7:7)** (BOEM, n.d.b; New Jersey Department of Environmental Protection, n.d.b). The NJDEP

reviews projects for their consistency with state coastal policies, which includes an evaluation of potential impacts on marine resources.

The state's approach is also heavily reliant on research. The NJDEP has published a "Review of the Impacts to Marine Fauna from Electromagnetic Frequencies" which notes that while some marine animals may be attracted to or repelled by EMF from cables, "published research shows no more than a negligible impact on those organisms" (New Jersey Department of Environmental Protection, n.d.c). The state's **Research and Monitoring Initiative (RMI)** is also designed to fill knowledge gaps regarding offshore wind, which includes studying the effects of EMF from export cables (New Jersey Department of Environmental Protection, n.d.d). While a specific numerical EMF standard is not cited in the regulations, the state's focus is on ensuring developers implement best practices, such as burying cables and choosing engineering designs that minimize the EMF field, to mitigate potential effects (New Jersey Department of Environmental Protection, n.d.e; BOEM, n.d.a).

5.6 Other Environmental Concerns

Beyond the major concerns of underwater noise, EMF, and animal collision, a range of other environmental and legal issues must be addressed for tidal and wave energy projects. These regulations are often found within broader statutes and permitting processes rather than in a single, dedicated law.

Federal Regulations

The federal government regulates tidal and wave energy projects primarily through the permitting authority of the **USACE** and the **Federal Energy Regulatory Commission (FERC)**. All projects, regardless of whether they are interconnected with the grid, are subject to permitting by the USACE under Section 404 of the Clean Water Act and Section 10 of the Rivers and Harbors Act (Maine.gov, n.d.). These permits are required for any "work" in navigable waters, which includes the construction of tidal and wave energy devices (U.S. Army Corps of Engineers, n.d.a). FERC issues licenses for hydrokinetic projects, which can last for 30 to 50 years, and includes a comprehensive review of environmental impacts (Federal Energy Regulatory Commission, n.d.).

Another significant area of federal regulation is the impact on vessel navigation and safety. The U.S. Coast Guard has authority over navigable waterways and would be involved in ensuring that tidal and wave energy devices do not obstruct navigation (NOAA Nautical Charts, n.d.). Developers are required to install appropriate aids to navigation, such as lights and buoys, to mark the location of the devices and to ensure the safety of vessels (NOAA Nautical Charts, n.d.). Furthermore, the regulations would consider the potential for gear entanglement, particularly for commercial fishing gear. While there are no specific numeric limits on entanglement, the project's design and location are scrutinized to minimize this risk (U.S. Army Corps of Engineers, n.d.a).

New Jersey State Regulations

In New Jersey, the NJDEP plays a critical role in regulating these projects, especially in state-owned tidelands. The state holds ownership of all lands that are flowed by the tide up to the mean high-water line (New Jersey Department of Environmental Protection, n.d.b). Therefore, any project on or within these tidelands requires a Tidelands License or Tidelands Lease from the NJDEP (New Jersey Department of Environmental Protection, n.d.b).

In addition, projects must comply with the state's **Public Trust Doctrine**, which ensures public access to the waterfront for fishing, navigation, and recreation (New Jersey Department of Environmental Protection, n.d.c). Tidal and wave energy projects must be designed and sited in a way that does not impede this public right of access, a consideration that is reviewed as part of the **Coastal Area Facility Review Act (CAFRA)** permit process (New Jersey Department of Environmental Protection, n.d.a; New Jersey Department of Environmental Protection, n.d.c).

Finally, the state is also concerned with the impact of these projects on existing infrastructure and other industries, such as commercial and recreational fishing. The NJDEP engages in collaborative efforts with various stakeholders to assess and mitigate these impacts (New Jersey Department of Environmental Protection, n.d.a). While a bill was introduced to establish specific goals for wave and tidal energy, the state's primary approach remains to evaluate projects on a case-by-case basis under its broad regulatory authority (New Jersey Legislature, n.d.).

6 Conclusion

This study delivers a high-resolution, device-level assessment of wave and tidal energy potential along the New Jersey coastline, providing a robust roadmap for site selection and infrastructure planning.

The core research questions were addressed through a multi-faceted approach:

Harnessable Energy Potential: The device-level analysis estimated harnessable tidal power potential ranging from 24 MW to 88 MW, depending on rotor size and location, significantly lower than past theoretical estimates due to practical constraints like device spacing, depth requirements, and environmental conflicts. Key tidal energy sites include Hudson River, Barnegat Bay, Cape May, and two additional Delaware River sites one near Trenton and another between Philadelphia and Wilmington—selected for their accessibility and reduced waterway use conflicts. For wave energy, four high-density areas off Atlantic City were identified, with approximately 25% of generating capacity capturable using 2 MW point absorbers, constrained by seasonal variability and offshore focus.

Regulatory and Policy Framework: The research underscores the need for a robust regulatory framework to ensure successful deployment. Federal agencies (e.g., BOEM, NOAA Fisheries) and state agencies (e.g., NJDEP) enforce comprehensive environmental reviews under statutes like the Marine Mammal Protection Act (MMPA), Endangered Species Act (ESA), and Coastal Area Facility Review Act (CAFRA). While no specific numerical standards exist for issues like electromagnetic fields (EMF) or noise, developers must adopt best practices, such as burying cables to mitigate EMF and implementing monitoring to minimize animal collision risks. Compliance with NJDEP's Tidelands License or Lease requirements and considerations for navigation and industries like commercial fishing further emphasize the need for conflict-free siting.

In conclusion, this report establishes a data-driven foundation for New Jersey's transition to a diversified, clean energy portfolio. It provides actionable recommendations for pilot projects at Hudson River, Barnegat Bay, Cape May, and the proposed Delaware River sites for tidal energy,

and offshore Atlantic City for wave energy, demonstrating technical feasibility, economic viability, and environmental responsibility. While onshore wave energy is not viable due to modeling limitations and wave attenuation, the offshore focus strengthens the case for marine renewables. These findings position New Jersey as a potential leader in mid-Atlantic marine renewable energy, offering policymakers, developers, and regulators a critical resource for advancing sustainable energy initiatives. Further research into long-term ecological impacts and stakeholder engagement is recommended to refine deployment strategies.

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