IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received 24 December 2025, accepted 28 January 2026, date of publication 3 February 2026, date of current version 10 February 2026.

Digital Object Identifier 10.1109/ACCESS.2026.3660824

RESEARCH ARTICLE

Integrating Marine Hydrokinetic and Offshore Wind Energy: A Review of Technologies, Deployment, and Challenges

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This work was the result of ''Overcoming Barriers to Marine and Hydrokinetic (MHK) Energy Harvesting in Offshore Environments, Center for Advanced Energy Studies'', under the CAES collaboration funds. Authored in part by Battelle Energy Alliance, LLC under Contract No. DE-AC07-05ID14517 with the U.S. Department of Energy. The future work will be supported by the Major Research Instrumentation Program (MRI) Award 2320619, which helped the acquisition of a state-of-the-art flagship digital real-time simulator, OPAL-RT

ABSTRACT Together, offshore wind (OSW) and marine hydrokinetic (MHK) technologies have the capacity to expand the world's access to abundant energy resources. With more than 83 GW of offshore wind energy capacity and 500 MW of ocean energy deployed globally by 2025, there is a significant amount of available resources; however, technical and non-technical challenges prevent the combined large-scale deployment of these technologies. There is still a lack of research that provides a parallel review of both MHK and OSW technologies in order to better understand their synergistic working principles. This paper aimed to address that research gap by presenting a comprehensive side-by-side review of the worldwide technological landscape, global deployment trends, integration strategies, and modeling approaches for MHK and OSW. A particular focus has been given on analyzing existing modeling and simulation techniques, assessing integration and control strategies, and comparing technologies based on water depth. Furthermore, this study provides important insights into the readiness levels of both technologies by highlighting ongoing international projects. This review aims to fill a significant gap in the literature and evaluate technological maturity, deployment viability, and integration limitations by comparing global MHK and OSW developments and using water depth as a comparison criterion.

INDEX TERMS Global deployment trends, integration and control strategies, marine hydrokinetic (MHK), modeling and simulation techniques, offshore wind (OSW).

I. INTRODUCTION

For centuries, flowing water has been used as a potential source of renewable energy. In recent years, growing technological innovations and the limitations of other renewable energy sources have reignited interest in marine renewable energy systems for sustainable energy generation. It is possible to speed up the shift towards a low-emission economy by integrating more marine renewable energy, as 500 megawatts of ocean energy were available worldwide in 2025 [1]. Additionally, by 2025, offshore wind (OSW) capacity grew to over 83 GW worldwide, with the United States, China, and Europe seeing the fastest expansion [2]. Marine energy installations are typically located offshore or in sizable inland water bodies like rivers and lakes, and they rely on integration with existing electrical grid networks to distribute the generated power. The term marine energy is occasionally used to describe offshore wind energy as well, which is derived from wind that blows across the ocean [3]. Marine energy is a reliable energy source, typically

The associate editor coordinating the review of this manuscript and approving it for publication was Meng Huang.

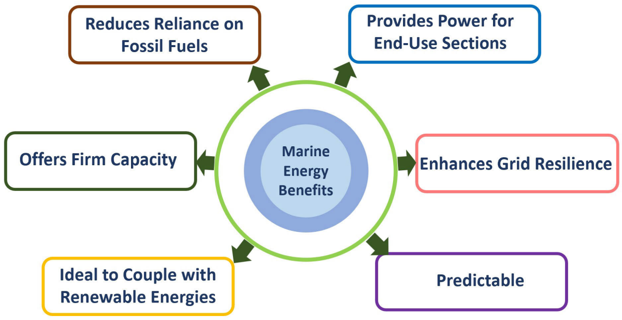


FIGURE 1. Key benefits of marine energy: predictable output, firm capacity, enhanced grid resilience, reduced fossil-fuel reliance, suitability for hybridization with other renewables, and service to end-use sectors [5].

located near areas where electricity is needed. It requires short transmission connections to support the resilience and dependability of the power system, and can power remote, coastal, and island communities [4]. Figure 1 shows some of the benefits of marine energy.

Combining OSW farms with marine hydrokinetic energy (MHK) could be an effective way to advance the development of both technologies because of the existing synergies between them. By sharing installations, improving energy resource predictability, smoothing power output, or expanding weather windows for maintenance and operation, it will facilitate easier installation and operation as well as better utilization of the marine resources [6]. They can also aid in expanding the wide range of energy-generating technologies available to a particular community, thus contributing to the resilience of the grid. Since they are typically installed in water, they can avoid land limitations, which is essential in island systems or developed coasts where the footprint of current renewable energy technologies may restrict projected fuel cost reduction targets [7]. The authors in [6] analyzed the current synergies between wave and OSW energy systems, with particular attention to the shielding effect of co-located wave energy converters, which results in larger weather windows for operation and maintenance tasks, and reduces the non-operational periods of wind turbines due to maintenance task delays, which is one of the challenges of this renewable energy source, especially when compared to onshore wind. Reference [8] proposed a new synergistic hybrid offshore energy platform that combines all feasible marine renewable energy harvesting devices with energy storage devices, which has advantages over traditional single-source energy systems, including increased energy yield per unit area and optimized use of available natural resources. The study done by [9] presented a roadmap for decision-makers to identify the best sites for combined OSW and wave energy farm developments, offering a thorough study of compiled and categorized data and research needs. A high-resolution numerical model, called Simulating Waves Nearshore (SWAN), has been performed in [10], and several case studies are used to analyze the power smoothing and shadow impact in co-located farms while taking into account actual sea conditions and operational wind farms. The results of the Interreg MED project Promoting innovative nEtworks and cLusters for mArine renewable energy synerGies in Mediterranean cOasts and iSlands (PELAGOS) were presented by the authors in [11]. The paper thoroughly discusses the key issues for the development of a Marine Renewable Energy cluster in the Mediterranean and demonstrates its necessity for the sustainable development of Blue Energy in the region, since Blue Energy development in the Mediterranean Sea is just getting started. With an emphasis on the integration of offshore wind farms employing advanced hybrid AC-DC and DC-DC conversion technologies, the study in [12] offered a thorough framework for smart microgrid systems. A novel Model Predictive Control (MPC) technique was presented that addressed important factors, such as wind farm layout and wake effects, while incorporating precise wind dynamics, such as speed, direction, and turbulence. For improved grid stability and dependability, the suggested framework integrated Battery Energy Storage Systems (BESS) and advanced protective mechanisms with both AC-DC and DC-DC conversion systems, as well as used a multi-layered strategy to address power conversion issues. A review of the literature on hybrid power systems (HPSs) using renewable energy sources has been provided, and appropriate control mechanisms have been proposed in [13]. It is evident from the study that RESs play a significant role in resolving the energy crisis, and the system stability is impacted by the RESs' characteristics, which cause oscillations in voltage and frequency that require reliable control methods. A suitable coordinating control mechanism is necessary for a system created with the aid of RESs and various Energy Storing Components (ESCs)., and this can be accomplished by choosing the right and clever soft computing algorithms, such as Particle Swarm Optimization (PSO), Genetic Algorithm (GA), Cuckoo Search Algorithm (CSA), and Mine Blast Algorithm (MBA). The authors concluded that the MBA-based 2DOF PID controller offers a high level of dependability and controllability across both practical and technical domains, thus making it a better choice for hybrid power systems management. In [14], a prototype for collecting data and identifying renewable resources such as wind and sea currents has been designed for operation. It provides a platform for testing intelligent control strategies and fault-diagnosis approaches, as well as for analyzing the stability behavior of such devices. By combining discrete wavelet transform (DWT) multi-resolution analysis with artificial neural networks (ANNs), authors in [15] proposed a fault detection and classification technique for multi-terminal high voltage direct current (MT-HVdc) lines. A four-terminal MMC-HVdc system is used to evaluate the dependable and intelligent processing capabilities of the suggested design. The evaluation confirmed that the suggested method correctly identifies healthy and defective circumstances and does not fall into over-fitting or under-fitting states. In order to enhance the response and precision of transient-based protection, a study by [16] suggested a DC-line fault diagnostic method based on a tuned long-short-term memory (LSTM) algorithm. The transient characteristics of DC-line voltages in the frequency-time domain are extracted using the discrete wavelet transform (DWT). Even when the noise influence is taken into account, a large number of both good and bad samples are used during training. The robustness of the suggested algorithm under different failure circumstances is assessed by running a large number of test samples after training. According to test results, the suggested algorithm has a high recognition accuracy of 98.6% and can identify DC defects. In [17], a unique AI-based dc fault location scheme for a meshed dc grid was developed. The optimal hyperparameters that enhance the performance of the chosen model while maintaining a low RMSE are found using the BO-based FFNN model with DWT application. For the selected multilayer FFNN model, weights and biases are adjusted during training using Levenberg–Marquardt backpropagation. The example studies demonstrate how effectively the suggested approach works with a variety of factors, including non-ideal noise occurrences, transmission line lengths, and various fault resistances. As a result, it can be used practically in the MT-HVdc grid.

Table 1 summarizes the literature discussed above and identifies the research gap:

Although there is plenty of current literature that focuses on various approaches of co-locating marine hydrokinetic energy and offshore wind technologies, there is a lack of research that thoroughly compares the two technologies side by side. Both of these technologies come with their own engineering and technological challenges, some of which include a lack of accurate resource characterization, scarcity of advanced ocean energy subsystem simulation and devices, power quality issues caused by grid integration, and operational and maintenance issues. Before deploying them together, it is essential to understand their working principles, current technologies, global deployment status, and how these technologies can realistically be made to work together in a way that improves system resilience.

To frame the scope and focus of this review, a few research questions were formulated to guide the comparative analysis throughout the journal. Particularly, this journal aimed to find answers to the following questions:

- What are the differences and similarities between MHK and OSW technologies?
- What is the current global deployment status for both MHK and OSW technologies, and how are they evolving?
- How do MHK and OSW technologies compare in terms of maturity, performance characteristics, and water depth?
- What are the technical challenges in terms of large-scale deployment of MHK and OSW?
- Which modeling, simulation, and control approaches are most common in the literature, and how do they support the design and operation of hybrid MHK–OSW systems?
- What are the most impactful and significant opportunities for future research direction?

This paper attempts to synthesize the existing research on MHK and OSW in order to provide a systematic review of current technologies, deployment approaches, and associated challenges. The contributions of this paper are listed below:

- A novel side-by-side comprehensive review of both marine hydrokinetic and offshore wind energy systems, covering their principles, current technologies, and global potential and deployment status with region-specific insights across North America, South America, Europe, Asia, and Australia, while also providing a list of ongoing projects worldwide.
- A comparative analysis of MHK and OSW technologies, highlighting the global offshore wind potential by region and depth, as well as feasible deployment technologies for both OSW and MHK systems based on water depth.
- Identification of technical challenges of large-scale deployment of MHK and OSW systems, including resource assessment, grid integration, technology maturity, operation and maintenance, deployment, and demonstration.
- A thorough discussion of co-location strategies, shared infrastructure models, and hybrid design approaches, as well as a review of advanced modeling frameworks, hardware-in-the-loop simulations, and real-world case studies to illustrate hybrid deployment and coastal grid support.

By comparing global MHK and OSW developments and incorporating water depth as a comparison criterion, this review aims to address a critical gap in the literature and assess technological maturity, deployment feasibility, and integration challenges.

The rest of this paper is organized as follows: Section I. A discusses the methodology used for the review, Section II reviews the principles and current technologies, and the global potential and deployment status of MHK technologies; similarly, Section III presents the corresponding discussion for OSW technologies; Section IV provides a comparative analysis of MHK and OSW Technologies, following by a thorough discussion on the technical challenges associated with their deployment in Section V; section VI provides a detailed discssuion on the integration framework and hybrid system development. Finally, Section VII concludes the paper by addressing the identified research gaps and suggesting future research directions.

A. METHODOLOGY

A structured narrative literature review approach was followed rather than a formal Systematic Literature Review (SLR) for this journal. The primary focus was to gather and analyze data on MHK and OSW technologies, emphasizing deployment status, water-depth dependence, technological

TABLE 1. Overview of the discussed literature review and the existing research gap in Marine hydrokinetic energy and offshore wind deployment. The table summarizes the contributions of each paper addressed above and identifies the research gaps in those studies.

Author Information	Contribution	Research Gap
S. Astariz [6]	Examined the synergies between offshore wind and wave energy systems, emphasizing the longer weather windows for operation and maintenance as well as the shielding effects of nearby wave energy converters.	Definite performance metrics and standardized comparison frameworks for co-located systems across different locations need to be included.
DOE WPTO Report [7]	Discussed the challenges of deploying renewable energy on land and suggested offshore hybrid systems as solutions for developed coastal areas and islanded systems.	Further research is needed on the potential of offshore hybrid systems.
L. Cui [8]	Proposed a new synergistic hybrid offshore energy platform combining all feasible marine renewable energy harvesting devices with energy storage devices, which showed increased energy yield per unit area and optimized use of available natural resources.	Large-scale validation and operational data are not available yet.
S. Hosseinzadeh [9]	Developed a decision-making roadmap for identifying optimal sites for combined offshore wind and wave energy farms using compiled and categorized datasets.	Site-selection methodologies need validation across diverse geographic regions and environmental conditions.
S. Astariz [10]	Performed high-resolution numerical modeling (SWAN) to analyze power smoothing and shadow effects in actual sea conditions and operational wind farms.	More study for validation at utility-scale deployments needed.
T.H Soukissian [11]	Presented results from the PELAGOS project, examining the development of marine renewable energy clusters in the Mediterranean region.	Region-specific studies: a cluster needs to be developed across various regions of the world.
M. O. Akhter [12]	Proposed a smart microgrid framework using hybrid AC–DC and DC–DC conversion technologies with model predictive control for offshore wind integration.	System-level scalability requires further research.
S. Ranjan [13]	Reviewed hybrid power systems using renewable energy sources and proposed coordinated control mechanisms to address voltage and frequency stability.	Unified control standards are needed for hybrid offshore renewable systems.
E. García [14]	Developed a prototype platform for offshore wind and wave data collection to support intelligent control and fault diagnosis strategies.	Extensive research is required before long-term and operational deployment.
M.Z. Yousaf [15]	Proposed a fault detection and classification technique for multi-terminal high voltage di- rect current (MT-HVdc) line by combining the discrete wavelet transform (DWT) multi-resolution analysis with artificial neural net- works (ANNs)	Further study is needed on experimental validation and real-world deployment studies of AI-based protection schemes.
M.Z. Yousaf [16]	Suggested a DC-line fault diagnostic method based on a tuned long-short-term memory (LSTM) algorithm and extracted the transient characteristics of DC-line voltages in the frequency- time domain using the discrete wavelet transform (DWT).	Extensive research is required before real-life implementation.
M.Z. Yousaf [17]	Developed a unique AI-based dc fault location scheme for a meshed dc grid.	Study on different topology types are missing.

maturity, and integration challenges. A flexible narrative method was used to organize both peer-reviewed research and authoritative technical reports that are extremely relevant to current industry and academic research, given the rapidly evolving, interdisciplinary nature of marine renewable energy research. The literature was collected through targeted searches across multiple institutional and academic sources, including:

- Google Scholar
- IEEE Xplore
- ScienceDirect
- Wiley Online Library
- Government and national laboratory reports:
    1) U.S. Department of Energy (DOE)
    2) Bureau of Ocean Energy Management (BOEM)
    3) National Renewable Energy Laboratory (NREL), currently known as National Laboratory of the Rockies (NLR)
    4) Pacific Northwest National Laboratory (PNNL)
    5) Global Wind Energy Council (GWEC)
    6) Water Power Technologies Office (WPTO)

Additionally, references cited in highly relevant papers were also analyzed to identify fundamental studies, important demonstration projects, and recent advancements not found in the initial searches. The review followed the following inclusion criteria:

- Studies addressing MHK and OSW technologies global deployment status
- Peer-reviewed journal articles, conference papers, and technical reports

- Research focusing on system integration, hybridization, and water-depth-dependence
- Publications on technical design, modeling, control strategies and commercial demonstrations

Moreover, the review followed the following exclusion criteria:

- Publications focused on economic analysis, market modeling, or cost-only studies
- Research work that discussed environmental or socio-economic aspects that is not linked to engineering or system-level integration
- Reports that mainly discussed regulatory frameworks, policy, or environmental impacts
- Reports published on DOE program management or funding structures without technical relevance

The main reason for these exclusion criteria was to maintain a clear technical focus and to perform a comparative engineering analysis in this particular journal. The review doesn't claim complete coverage of all published literature as this study does not follow a formal Systematic Literature Review (SLR). Rather, it emphasizes the technical aspects of MHK and OSW technologies, with the goal of offering a thorough, application-focused review that will shape further study and research direction.

II. MARINE HYDROKINETIC (MHK) ENERGY SYSTEMS

A. PRINCIPLES AND CURRENT TECHNOLOGIES

Marine energy, known as ocean energy, is a renewable energy source that harnesses the natural movement of water, encompassing wave, tidal stream, tidal range, offshore wind, ocean thermal, ocean current, run-of-river, and salinity gradients [18], [19], [20]. Among several hydrokinetic sources, harnessing the energy of nearshore and offshore waves is considered to offer the highest potential for energy production [21]. Hydrokinetic energy converters (HECs) utilize kinetic energy from three primary sources: inland waterways such as rivers, tidal flows in estuaries and channels, and oceanic currents. To date, the majority of research and technological advancement in HECs has concentrated on tidal energy systems, while inland and ocean current applications remain comparatively underdeveloped. Figure 2 illustrates the overall framework of a hydrokinetic system.

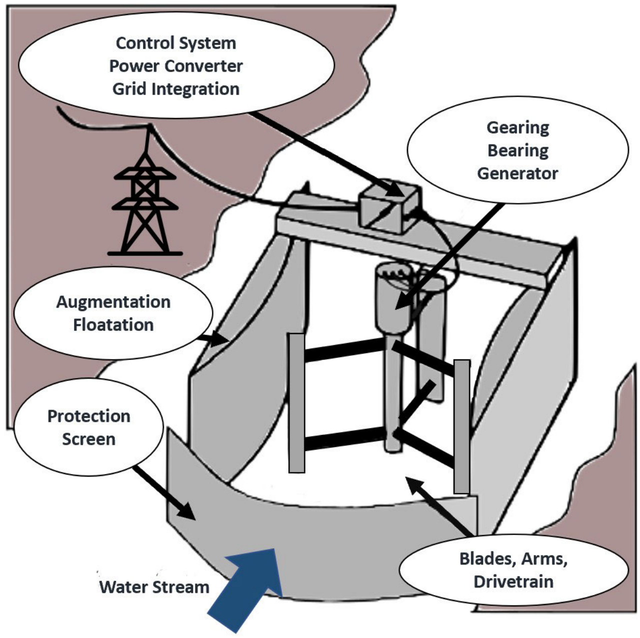


FIGURE 2. The figure shows a hydrokinetic electromechanical device positioned within a body of water, which converts the kinetic energy of water flow into electrical energy. A water stream enters through a protection screen and flows toward a rotor assembly comprising blades, arms, and a drivetrain. The upper part of the structure contains components for gearing, bearings, and a generator. Additional labels indicate augmentation floatation on the left side of the device, as well as a control system, power converter, and grid-integration unit located above the structure [22].

A hydrokinetic energy conversion system typically consists of a hydrokinetic turbine, a Permanent Magnet Synchronous Generator (PMSG), a power electronics converter, and either an energy storage unit or a grid-tie module, as shown in Figure 3.

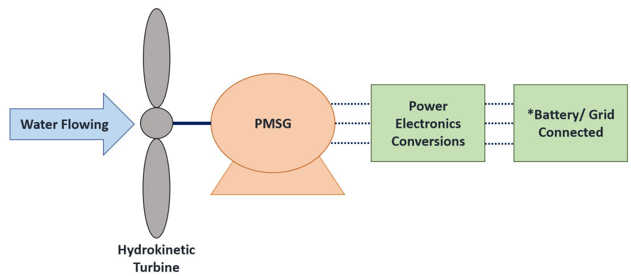


FIGURE 3. A hydrokinetic turbine driven by flowing water is connected to a permanent-magnet synchronous generator (PMSG), which converts mechanical energy to electrical energy through a power-electronics conversion stage. The converted electrical output is then supplied to a battery storage unit or to the grid [22].

The turbine can be turned at a specific speed by the flowing water. Without the need for a gearing system, the PMSG rotor is directly connected to the turbine shaft, and the movement rotates the generator rotor on its own. The power electronics conversion system regulates and transforms the output power from the PMSG. Three-phase rectifiers are used in stand-alone systems to convert a variable AC three-phase system to a variable DC voltage. The fluctuating DC voltage is then changed into a constant DC bus voltage by the DC-DC converter. The grid-tie connection technology, on the other hand, uses an inverter to transform the continuous DC bus voltage into AC power before sending it to the grid system [22]. The water density (ρ), turbine power coefficient, cross-sectional area, and water velocity all affect how well hydrokinetic turbines produce electricity [23], [24]. The ideal formula of kinetic energy in a hydrokinetic system can be derived from the following equations [22], [25].

$$\text{Kinetic Energy, } KE = \frac{1}{2} m V^2 \tag{1}$$

where, m = Mass, V = Stream Velocity

$$\text{Mass}, m = \rho AVt \tag{2}$$

where, ρ = Water density (1000 kg/m^3), t = time

$$\text{Area}, A = \pi R^2 \tag{3}$$

where, R = Blade Radius

The energy generated by a hydrokinetic turbine can be found by substituting equation 1 into equation 2,

$$E = \frac{1}{2}\rho AtV^3 \tag{4}$$

The power delivered by a hydrokinetic turbine,

$$P_m = \frac{1}{2}\rho AV^3 \tag{5}$$

where, P_m = Power developed by the rotor

But considering losses, a hydrokinetic turbine can only harness a portion of this power, and equation 5 can be modified into the following form [26]:

$$P_m = \frac{1}{2}\rho AC_P V^3 \tag{6}$$

where, C_p = Power coefficient of the turbine

The power coefficient, C_p, is the proportion of mechanical power the turbine can extract from the fluid stream, taking into account its efficiency. The Betz limit, a research done by Betz, is the theoretical maximum power that can be collected from a fluid flow, which is roughly 16/27 = 0.592, or 59% (theoretical maximum power available). C_p typically ranges from 0.25 to 0.3 for wind generators and small-scale river turbines. Highly efficient machines with low mechanical losses are subject to the upper limit. C_p is expected to be between 0.35 and 0.5 for marine turbines [22], [24], [26].

Additionally, the turbine's power coefficient C_p depends on the tip-speed ratio (TSR), defined as the ratio of the blade-tip linear velocity to the water-flow velocity [22].

$$TSR, \lambda = \frac{\omega_m R}{V} \tag{7}$$

where, ω_m = Turbine rotational speed

Figure 4 shows power efficient, C_p for different rotor designs [27].

MHK devices can be classified into two main categories [19]:

- **Tidal energy converters:** Tidal energy converters are underwater devices that resemble turbines, utilizing the tides or tidal currents to generate energy. The turbines rotate, just like wind turbines, as currents flow by. The devices are connected to wires that connect to an electrical grid in order to capture MHK energy [19]. Tidal energy can be harvested in three general ways: Tidal stream generators, Tidal barrages, and Tidal lagoons [28].
- **Wave energy converters:** Wave Energy Converters (WECs) are devices that harness the kinetic and potential energy of ocean surface waves, transforming them into mechanical or electrical power. They can supply emissionless energy for the electrical grid and a variety of additional uses, such as pumping for saltwater desalination or propulsion for marine vehicles. The seven most widely used types of wave energy converters are given below: Point absorbers, Terminators, Attenuators, Oscillating wave surge, Oscillating water column, Submerged pressure differential, Rotating mass [29].

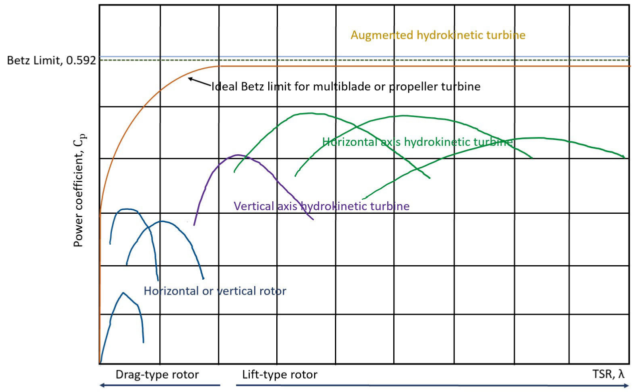


FIGURE 4. **Relationship between power coefficient and tip-speed ratio across hydrokinetic turbine designs. In addition to the Betz limit and optimal propeller-type performance trend, the figure compares C_p- λ curves for drag-type and lift-type rotors, as well as vertical-axis, horizontal-axis, and augmented hydrokinetic turbine designs [27].**

Figure 5 illustrates the MHK development and deployment time-line and the complete R&D technological strategy [30].

B. MARINE HYDROKINETIC ENERGY: GLOBAL POTENTIAL AND DEPLOYMENT STATUS

MHK technologies are witnessing a wide range of adoption worldwide, and Figure 6 illustrates the projected worldwide marine energy market size from 2024 to 2034 by region [31].

The following subsections provide a detailed overview of global MHK deployment scenarios.

1) NORTH AMERICA

MHK energy in the United States holds significant untapped resources with vast potential to support the nation's transition towards renewable energy-dominated power systems, as the demand for expanding energy abundance and enhancing energy security is growing. The U.S. coastline and river systems possess substantial MHK resources with high power densities, many of which are situated near densely populated coastal areas, which facilitates reduced transmission losses, improves grid stability, and minimizes the need for extensive infrastructure development. Specifically, the strongest wave resources are found in Alaska, Hawaii, and the west coast of the United States [32]. Figure 7 shows the technical power potential of U.S.A marine energy resources [33].

Table 2 shows a breakdown of the technical power potential of marine energy resources in the United States by resource

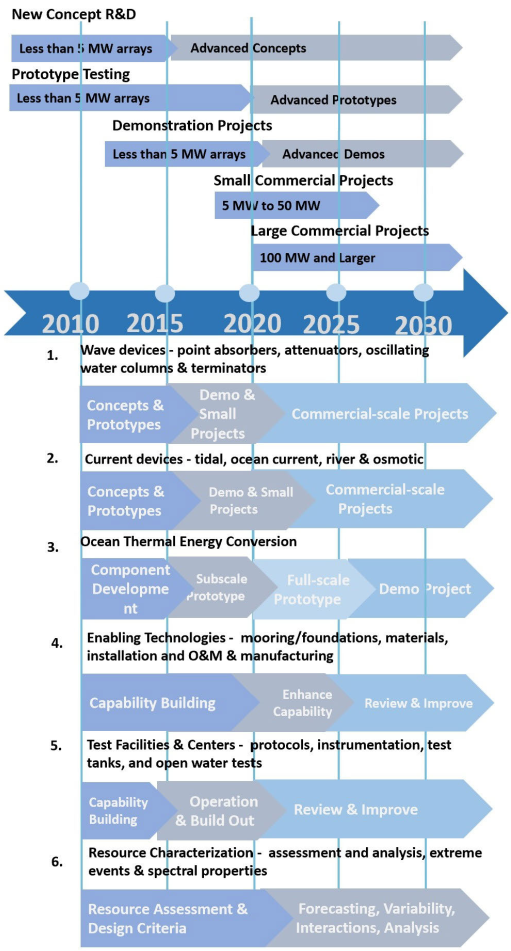


FIGURE 5. MHK development and deployment time-line and the R&D technical strategy, from prototype testing in 2010, large commercial projects have started being deployed from 2020 onwards. The figure also highlights the estimated timeline for developing test facilities and capabilities needed for MHK development [30].

type, including estimated annual energy yield, equivalent number of homes powered, and contribution to national electricity generation.

Although the theoretical resource potential for MHK energy in the United States is substantial, the practically attainable energy is reduced when accounting for technological constraints in energy conversion efficiency [34], [35]. Large-scale deployment remains limited, and the pace of commercialization is significantly slower than the resource potential might suggest. Most deployments have been restricted to short-term, single-device trials, which limit understanding of long-term reliability and system-level integration.

Technology Readiness Levels (TRLs), shown in Figure 8, a measure adopted by the U.S. Department of Energy (DOE), are used to evaluate the technological maturity of a specific field [36]. They define the relative advancement of particular concepts, designs, and initiatives, and decide if projects are eligible for specific levels of development financing. Ocean current MHK energy technologies typically fall within this scale's TRL 1–5 range. Most commercial projects are either in the design stage or small-scale demonstration/

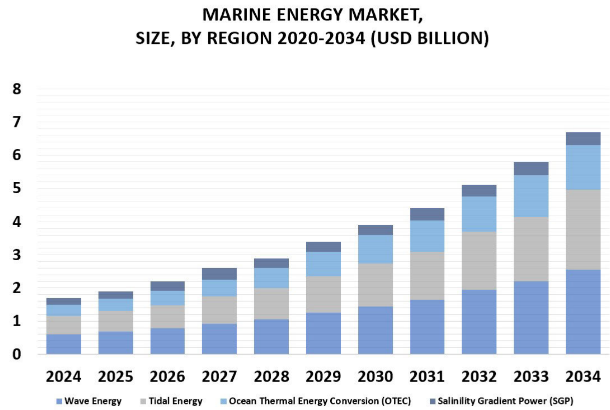


FIGURE 6. Projected global marine energy market size by technology type from 2024 to 2034 (USD billion). The stacked bars show the estimated annual market value contributions from wave energy, tidal energy, ocean thermal energy conversion (OTEC), and salinity gradient power (SGP). While wave and tidal energy show the most significant and fastest-growing shares over the projection period, indicating relatively higher technology maturity and deployment activity, OTEC and SGP show smaller but steadily increasing shares as emerging technologies [31].

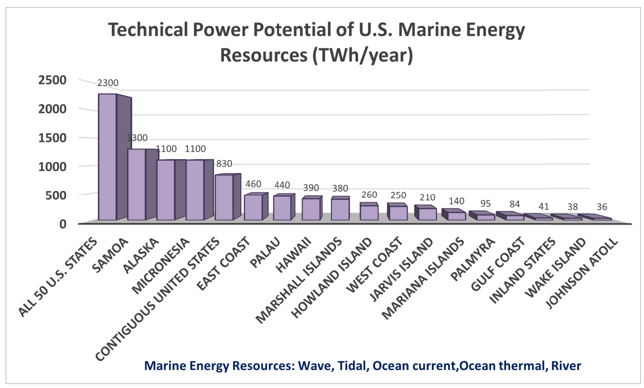


FIGURE 7. Estimated technical power potential of U.S. marine energy resources by regions, expressed in terawatt-hours per year, with the largest contributions from Samoa (1,300 TWh/year), Alaska, and Micronesia (1,100 each TWh/year). Resources include wave, tidal, ocean current, ocean thermal, and river [33].

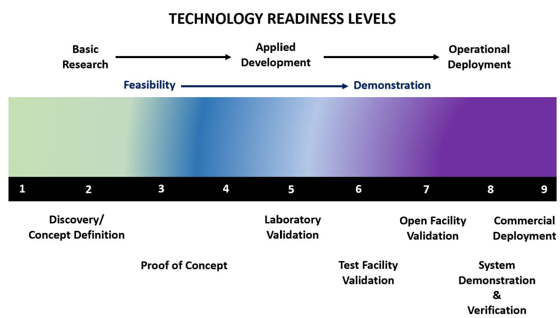


FIGURE 8. Technology readiness levels (TRLs) for marine energy systems describe the development of marine energy technologies from basic research to commercial deployment. TRL 1–3 spans from basic research to proof of concept; TRL 4–6 includes laboratory and test facility validation during applied development; and TRL 7–9 involves open-facility testing, system demonstration, and commercial operation [36].

TABLE 2. Summary of estimated annual technical resource availability for major U.S. marine energy categories, including wave, tidal, ocean current, ocean thermal, and riverine resources, along with corresponding estimates of homes that could be powered and the share of U.S. electricity generation each resource represents [33].

Resource Type	Technical Resource (TWh/yr)	Homes Powered	U.S. Electricity Generation (%)
Wave (to Exclusive Economic Zone (EEZ))	1,400	130,000,000	34
Tidal	220	21,000,000	5.4
Ocean Current	49	4,600,000	1.2
Ocean Thermal	540	51,000,000	13
River	99	9,300,000	2.4
Total	**2,300**	**220,000,000**	**57**

proof-of-concept testing, and no ocean current prototype devices have been tested in a suitable setting.

Table 3 provides a brief overview of ongoing and completed marine hydrokinetic projects in the U.S.

The DOE has renewed its partnership with Norway's Royal Ministry of Energy to extend collaboration in water power research and development, which builds on the five-year memorandum of understanding (MOU) Annex signed in 2020, and connected the DOE's Water Power Technologies Office with the Norwegian Research Centre for Hydropower Technology. Under the updated agreement, both parties will exchange key knowledge, tools, and technologies aimed at overcoming barriers to the development, testing, and advancement of marine energy and next-generation hydropower technologies [43].

Furthermore, the DOE Water Power Technologies Office funds university-based National Marine Energy Centers (NMEC), which anchor U.S. marine-energy research and development. Each center creates talent pipelines that directly contribute to the expanding ocean economy, establishes regional connections, and offers open-access testing facilities. In addition to reducing the cost and risk of technology development, the NMECs also help the U.S. compete in the global marine energy race by tying federal R&D funding to regional economies and integrating research infrastructure at reputable academic institutions. Table 4 briefly discusses the four NMECs that are currently conducting research on various marine energy resources and technologies [44].

Canada possesses world-class test facilities, extensive marine renewable energy resources, and existing human and capital assets in the energy and marine sectors, as shown in Figures 9.

With an estimated 40,000 megawatts of potential, Canada's tidal energy resource could replace the carbon emissions from 24 million cars and provide emission-free electricity

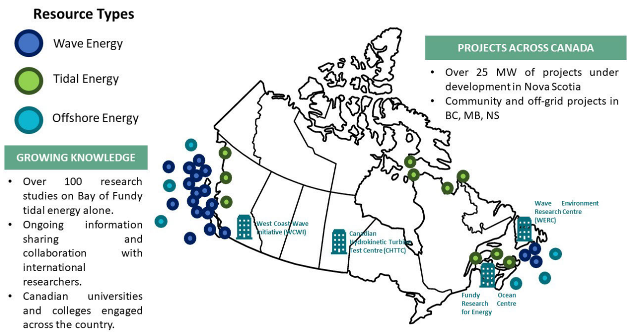


FIGURE 9. Map highlighting marine renewable energy resources and major project sites in Canada; wave energy resources are illustrated in blue, tidal energy in green, and offshore wind energy in teal, showing active research hubs and test facilities in universities and colleges, as well as regional project development [45].

for 12 million households. These are some of the ongoing projects and organizations in Canada [45].

- Acadia Tidal Energy Institute [46].
- Canadian Hydrokinetic Turbine Test Centre [47].
- Fundy Ocean Research Centre for Energy (FORCE) [48].

Among them, FORCE [48] is Canada's top research institute for tidal stream technology, located in Mi'kma'ki, and provides offshore and onshore electrical equipment to connect devices to the power grid.

2) SOUTH AMERICA

The Paraná River basin in the South region is home to the majority of Brazil's hydroelectric reservoirs, including the Itaipu plant, the world's second-largest hydroelectric power plant with a 14 GW capacity [49]. The majority of the country's hydroelectric power stations are located in the Midwest, South, and Southeast. The few studies done on ocean renewable energy along the Brazilian coastline have mainly concentrated on the energy from waves and ocean currents in particular areas.

Chile is well-positioned to utilize its marine renewable energy resources because of its more than 4,000 km of Pacific coastline, and has an overall wave resource that is probably greater than 200 GW, but estimates vary. According to UK marine energy experts Aquatera, Chile may build more than 300 MW of wave power-producing capacity by 2030 with the correct support policies [50]. The Municipality of Chile Chico in Chile signed an agreement with Ocean Renewable Power Company (ORPC) and its wholly-owned subsidiary, ORPC Chile in 2023, to install a RivGen Power System near the intersection of General Carrera Lake and Bertrand Lake, and the first device would be connected to the regional grid network of the Edelaysen utility [51].

There is a lot of potential for the development of marine renewable energies, mostly tidal and wave energy, along the long Argentine coastline in the South Western Atlantic Ocean [52].

TABLE 3. Summary of major U.S. marine hydrokinetic (MHK) projects, including their locations, key technical features, TRL metrics, and assigned Technology Readiness Levels (TRLs). Project information and TRL classifications are compiled from publicly available data reported by RivGen Power System, ORPC [37], [38], Verdant Power [39], Oscilla Power [40], [41], and the Ocean Energy Buoy [42].

Project Name	Location	Key Features	Metrics	TRL
RivGen Power System, ORPC [37, 38]	Village of Igiugig, Alaska	The longest operating marine energy project in America; operates stably in isolated and rural locations; connects to off-grid systems without affecting the community's access or dependability of electricity	Full-scale Operation	9
	Eastport-Lubec, Maine	A prototype with an output of 25 kW at a water flow velocity of 2 m/s	Full-scale Operation	9
	Millinocket, Maine	A two-unit Modular RivGen array; demonstrates potential to provide steady, resilient baseload for EV charging and critical services	Demonstration	7
	Lower Mississippi River, Louisiana	For deployment as a technology demonstration at a Shell facility, aims to provide Shell's onshore operations with steady renewable electricity	Demonstration	7
Roosevelt Island Tidal Energy (RITE) Project, Verdant Power [39]	East River, New York	Utilizes Free Flow System and Tri Frame Mount of Verdant Power; produces clean energy from the natural tidal currents	Commercially licensed	9
Triton-C Wave Energy Converter, Oscilla Power [40]	Wave Energy Test Site (WETS), Hawaii	A 100 kW system built for secluded communities, or isolated power-at-sea applications	Test Facility Validation	6
Triton Wave Energy Converter, Oscilla Power [41]	Castine, Maine	A 1/6 scale prototype of 1 MW Triton wave energy converter	Demonstration	7
Ocean Energy Buoy [42]	Hawaii	A 1.25-MW wave-energy buoy to be moored at a 60-m-deep berth, engineered to withstand gale-force winds and extreme seas	Open Facility Validation	7

TABLE 4. The four U.S. National Marine Energy Centers (NMECs), with their establishment year and principal research focus on marine energy resources and technologies [44].

Energy Center Name	Start Date	Focus Area
Atlantic Marine Energy Center (AMEC)	2021	Focuses on improving energy resilience and sustaining the blue economy, marine energy research and technology development is being conducted in estuarine, tidal, and wave environments around the Atlantic coast.
Hawai'i Marine Energy Center (HMEC)	2009	Emphasizes on ocean thermal energy conversion (OTEC) and wave energy, as its Pacific location grants year-round access to reliable ocean resources, and makes it perfect for tropical applications and long-duration marine energy installations.
Pacific Marine Energy Center (PMEC)	2008	Facilitates wave, tidal, and river energy research and is home to the first full-size, grid-connected, open-ocean wave energy test site in the country, PacWave South, situated off the coast of Oregon.
Southeast National Marine Renewable Energy Center (SNMREC)	2010	Prioritizes the growth of ocean current energy, especially from the Gulf Stream, as well as provides infrastructure and data services that facilitate the transition of technologies from concept to ocean trial, supporting wave energy research and offshore sensing systems.

3) EUROPE

With the European Union (EU) leading global development and targeting 100 GW of combined wave and tidal capacity by 2050, ocean energy has gained momentum [53]. As per the most recent market analysis, the European market accounts for 24.26% of the global market revenue in 2025 [54].

The European Marine Energy Centre (EMEC) Ltd is the first and foremost facility in the world for testing and demonstrating wave and tidal energy converters, which are technologies that use the power of tidal streams and waves to create electricity, in the ocean [20]. Some significant recent projects include [55]:

- **France's Seaturns point absorber:** TRL 6, tested in 2024,
- **Wavepiston's oscillating surge converter in Spain:** TRL 8, connection with energy collectors completed in 2025,
- **CorPower's C4 point absorber in Portugal:** TRL 7, ready for redeployment, and
- **Netherlands' Slow Mill device:** Dry testing 2024, expected operation 2025.

Figure 10 illustrates the annual and cumulative energy capacity of tidal stream and wave energy in Europe [56], while Figure 11 presents the total operational capacities for these technologies in the European Union and the United Kingdom in 2024 [56].

4) ASIA

By the end of 2025, the marine energy sector in Southeast Asia is expected to generate 12.41k kWh of electricity [58].

With 14.4 GW of additional installed capacity in 2024, bringing the total to 435.95 GW, China remains the leader in hydropower development in East Asia and the Pacific. The Special Funds for Marine Renewable Energy (SFMRE), the largest special funding project in history for tapping MRE, was created by the Chinese government to encourage the development and use of MRE [59], and China's hydropower

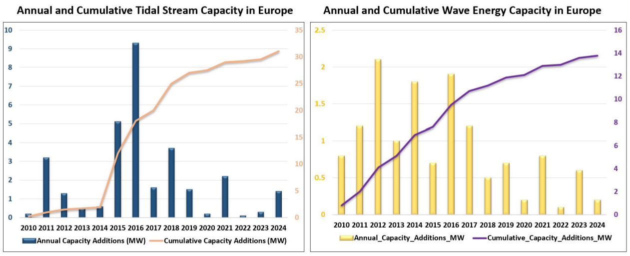
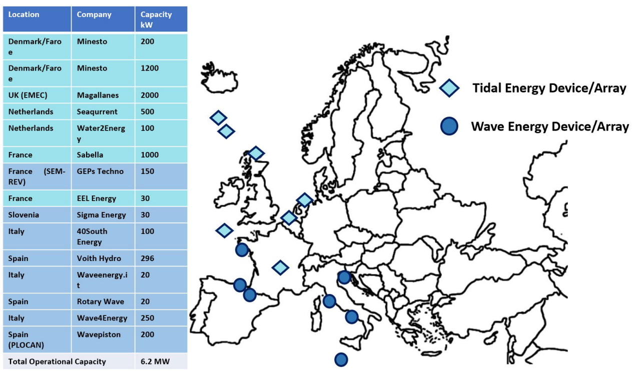


FIGURE 10. **Annual and cumulative tidal stream (left) and wave energy (right) capacity additions in Europe from 2010 to 2024. Annual capacity additions are shown using bar plots (tidal: blue; wave: yellow), while cumulative capacity additions are shown using line plots (tidal: orange; wave: purple). Data show a consistent rise in the deployment of wave technologies from 2012 to 2016 and tidal technologies from 2015 to 2017. Cumulative capacity continues to increase, showing ongoing project demonstration and technology development across the European marine energy sector [57].**



Location	Company	Capacity kW
Denmark/Faroe	Minesto	200
Denmark/Faroe	Minesto	1200
UK (EMEC)	Magallanes	2000
Netherlands	Seaqurrent	500
Netherlands	Water2Energy	100
France	Sabella	1000
France (SEM-REV)	GEPs Techno	150
France	EEL Energy	30
Slovenia	Sigma Energy	30
Italy	40South Energy	100
Spain	Voith Hydro	296
Italy	Waveenergy.it	20
Spain	Rotary Wave	20
Italy	Wave4Energy	250
Spain (PLOCAN)	Wavepiston	200
Total Operational Capacity		6.2 MW

FIGURE 11. **Operational marine-energy demonstrators in 2024 in Europe: map of tidal (diamonds) and wave (circles) device/array sites with representative capacities by company (left table); total operational capacity across listed sites is 6.2 MW [55].**

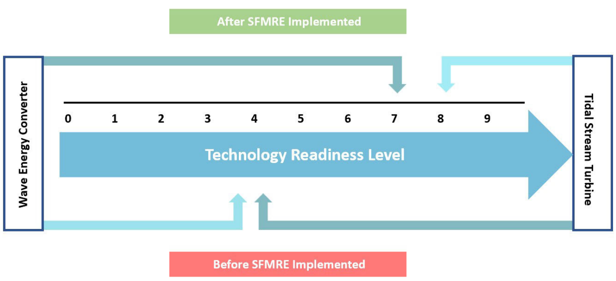
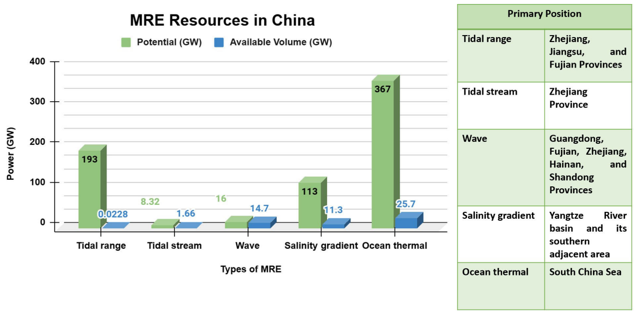


FIGURE 12. **Comparison of the maturity of marine renewable energy (MRE) technologies in China before and after the implementation of SFMRE. The diagram highlights the advancement in technology readiness levels (TRL) for tidal stream systems and wave energy, and the contrast in the TRL positions before policy support and the expedited progress observed afterward [59].**

capacity reached 319 GW at the end of 2015, growing at a pace of 4.9% [60]. Figure 12 shows the MRE technological maturity level in China and Figure 13 shows the potential and available volume of MRE in China.

The first tidal trial project in Japan was started in 2019 at the Goto Archipelago, off the coast of Nagasaki Prefecture. In 2021, the 500-kW tidal turbine began commissioning, exporting about 242 MWh of total energy production in just



Primary Position	
Tidal range	Zhejiang, Jiangsu, and Fujian Provinces
Tidal stream	Zhejiang Province
Wave	Guangdong, Fujian, Zhejiang, Hainan, and Shandong Provinces
Salinity gradient	Yangtze River basin and its southern adjacent area
Ocean thermal	South China Sea

FIGURE 13. **Marine Renewable Energy Resource Profile in China. Bar charts compare technical potential (green) and available volume (blue) in GW for tidal range, tidal stream, wave, salinity-gradient, and ocean-thermal resources; while the table presents the primary resources by regions [59].**

eight months [61]. The AR1100 tidal turbine, installed by Proteus Marine Renewables, is the first megawatt-scale grid-connected tidal energy system in Japan. The 1.1 MW tidal energy produced by the turbine, which will be installed in the Naru Strait, would fasten Japan's transition to renewable energy sources and reduce fuel costs for the Goto Islands' electrical supply [53].

5) AUSTRALIA

Most of Australia's best wave energy resources are found in the southern coast, stretching from Geraldton, Western Australia, including the beaches of South Australia and Victoria, to the southernmost point of Tasmania. [62]. By 2050, wave energy resources in this area are predicted to provide up to 11% of Australia's energy requirements. Successful wave energy projects, such as Wave Swell Energy's King Island deployment and Carnegie's Garden Island project, have been funded mainly by the Australian Renewable Energy Agency (ARENA). Additionally, the Clean Energy Finance Corporation (CEFC) provides funding for wave energy and other renewable energy projects. With only a few laboratory-scale facilities now available, Australia still lacks national grid-connected wave energy test centers [63]. Figure 14 shows the wave energy projects developers on the coastline of Australia [64].

Table 5 summarizes the global MHK deployment scenarios.

III. OFFSHORE WIND (OSW) ENERGY SYSTEMS

A. PRINCIPLES AND CURRENT TECHNOLOGIES

Offshore wind energy refers to the power captured by wind turbines from winds blowing over bodies of water, where the force of the winds at sea is converted into electricity and supplied to the onshore grid [65], [66]. In contrast to traditional power plants, a wind turbine uses the emissionless, abundant power of the wind to rotate magnets inside a coil of conductive wire in order to produce electricity [66].

The top portion of the turbine is pointed toward the wind, the three blades are positioned at precisely the right angle, and the airflow through them rotates the blades to harness

TABLE 5. **Comparative overview of global marine hydrokinetic energy deployment scenarios. Table highlights the prominent MHK technologies, technical potential, main advantages, and deployment status across various countries in the world; the projects span from laboratory-scale testing to ongoing demonstration.**

Region	Prominent MHK Technologies	Technical Potential (Estimated)	Main advantages	Deployment Status
North America (United States, Canada)	Wave, Ocean thermal, Tidal	Significantly high	Vast and reliable resource potential, Lot of prototype testing facilities and national test centers	Concept to ongoing demonstration projects
South America (Brazil, Chile, Argentina)	Wave and tidal	Medium to high	Well-positioned resources, High wave power capacity	Devolvement stage
Europe	Wave and tidal	High	Strong policy support and grid-connected demonstrations	Facility testing to deployment
Asia (China, Japan)	Tidal	High	Significant amount of predictable and reliable resource	Pilot projects and large-scale deployment
Australia	Wave	High	Reliable testing facilities	Laboratory scale testing

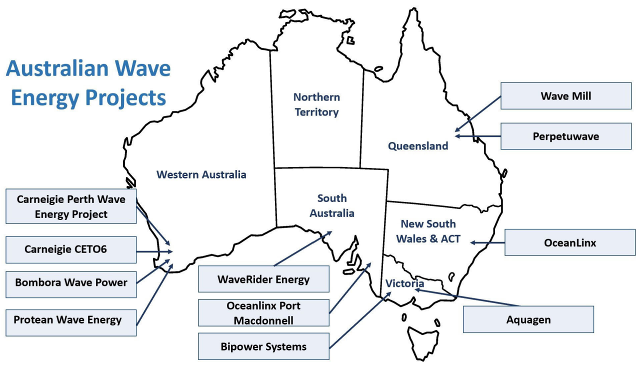


FIGURE 14. **Geographical distribution of notable wave-energy projects along the Australian coastline, categorized by state. Major demonstration and commercial projects are highlighted on the map, including Carnegie's Perth Wave Energy Project and CETO6 in Western Australia, WaveRider Energy and Bipower Systems in South Australia, OceanLinx in New South Wales, Aquagen in Victoria, and Perpetuwave and Wave Mill in Queensland [64].**

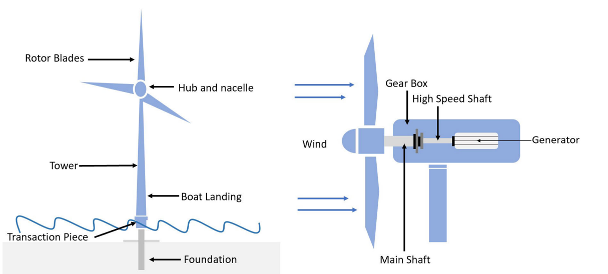


FIGURE 15. **Operating principle and structure of an offshore wind turbine; the figure on the left shows the front view consisting of the rotor blades, hub and nacelle, tower, transition piece with boat landing, and foundation for the installation; while the figure on the right shows the sectioned side view comprising gear box, main shaft, high speed shaft, and generator [66].**

wind energy. The blade motion is transmitted by a driving shaft, frequently by a gearbox, that turns magnets inside a coil of wire inside the nacelle, the non-rotating portion of the turbine's top, which produces alternating current of electricity [66]. Figure 15 illustrates this.

Power from each wind turbine is sent to an offshore substation through wires that run down the tower and beneath

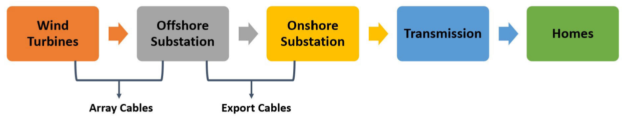


FIGURE 16. **Flow diagram of electricity generation and delivery in an offshore wind farm. Power generated from the wind turbines is collected through array cables and sent to the offshore substation. Export cables transmit the power to an onshore substation for further conversion and integration into the transmission network before distribution to end users [66].**

the ocean floor, where high-voltage cables are used to step up the energy to a greater voltage so it can be sent ashore. In order for the electricity to be put into the grid and delivered by power lines to the residences and businesses that use it, another substation on the land must once more modify the voltage [66], shown in Figure 16.

Two main types of offshore wind energy are described below [65]:

- **Fixed-Bottom Offshore Wind Energy:** These are the ones in which the foundation that holds the wind turbine's tower, a support structure, is connected straight to the ocean floor. Because of their special design and installation, they are usually placed in water up to 60 meters deep.
- **Floating Offshore Wind Energy:** These use buoyant platforms that rest on the water's surface and are secured to the seabed with long mooring lines, enabling their deployment in water depths exceeding 60 meters.

Table 6 describes the recent foundation technologies used for offshore wind projects [45].

Figure 17 shows the OSW construction and installation time-line from 1986 to 2024 [67].

B. OFFSHORE WIND ENERGY: GLOBAL POTENTIAL AND DEPLOYMENT STATUS

Offshore wind is expected to play a vital role in the worldwide energy movement, bringing about remarkable transformations in contemporary power systems, and Figure 18 presents

TABLE 6. Overview of offshore wind turbine foundation types, including monopile, gravity-based, and tripod designs, with brief descriptions of their structural characteristics and installation process [45].

Foundation Type	Description
Mono pile	A steel piling pushed into the seafloor around 10 to 20 meters deep.
Gravity	The most popular offshore wind foundation is a sizable steel or concrete base that sits on the ocean floor and is supported by gravity.
Tripod	Depending on the soil, tripod piles, which are based on technology from the oil and gas sector, are normally driven 10 to 20 meters into the seabed.

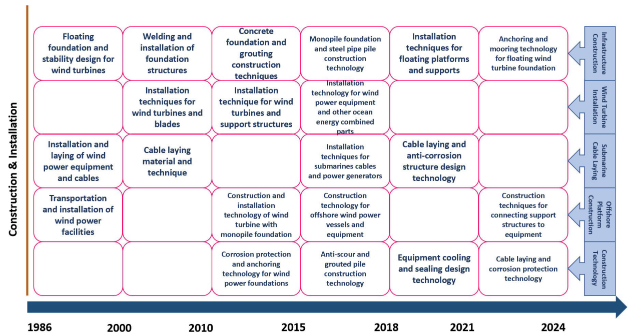


FIGURE 17. OSW construction and installation technology time-line, illustrating the continuous evolution of turbine installation methods, foundation systems, electrical infrastructure, as well as support technologies from 1986 to 2024. The figure highlights the increasing technical complexity and diversification of OSW construction practices as projects extended into deeper waters and larger commercial deployments over time [67].

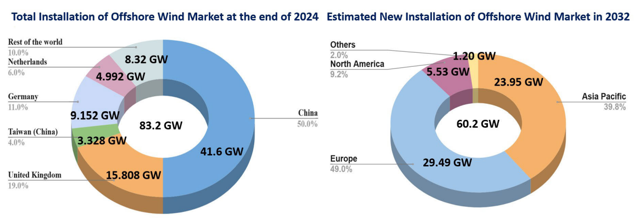


FIGURE 18. Global offshore wind deployment: total installed capacity by country/region at the end of 2024 was 83.2 GW (left), which is anticipated to double by the end of 2025, estimated new installations in 2032 totaling 60.2 GW (right) [69], [70].

the new offshore wind installations at the end of 2024 and estimated new offshore wind installations in 2032 [68], [69].

Figure 19 shows operating worldwide offshore wind farms as of April 2025 [71].

1) NORTH AMERICA

The development and operating pipeline for offshore wind energy projects in the United States reached a potential generating capacity of 80,523 MW by May 31, 2024, and currently, four projects are completely operational in the U.S. wind energy pipeline. The 132-megawatt South Fork Wind Farm, the nation's first commercial-scale offshore wind power station, started supplying electricity to New York in November 2023 and was put into full operation on March 14, 2024 [69]. As shown in Table 7, the U.S. offshore wind pipeline spans a wide range of development stages, from four operating projects to more than sixty early-stage proposals.

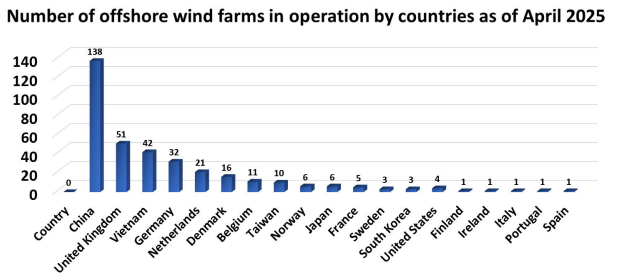


FIGURE 19. Number of offshore wind farms in operation worldwide by country as of April 2025. The figure displays national deployment, highlighting China as the global leader with the highest number of operational offshore wind farms, followed by the United Kingdom, Vietnam, and Germany. At the same time, the Netherlands, Denmark, Belgium, and Norway show medium deployment and rising markets, while the United States, South Korea, and Japan have smaller but growing offshore wind farms [71].

TABLE 7. Summary of U.S. offshore wind development pipeline by stage as of September 2025, highlighting stage in development pipeline, project name, along with capacity in MW. A total of four projects are in the operational stage, three are under construction, and work orders have been stopped for two projects.

Stage in Development Pipeline	Project Names and Capacity (MW)
Operating [69]	Block Island Wind Farm (30 MW), Coastal Virginia Offshore Wind Pilot (12 MW), South Fork Wind Farm (132 MW), Vineyard Wind 1: partially operating (800 MW) [72].
Under Construction	Coastal Virginia Offshore Wind (2587 MW), Sunrise Wind (924 MW), Empire Wind 1 (810 MW) [73].
Permitting (Construction and Operations Plan submitted)	New England Wind, South Coast Wind; multiple projects have submitted COP to BOEM; power offtake contracts secured.
Site Control	Leasing rights to developers; technical potential of almost 22,871 MW.
Proposed Lease Areas	Total capacity 29,995 MW.
Proposed State Projects	Floating demo project (California); others in early stage.
Without permits [73]	Starboard Wind (1,184 MW), Beacon Wind (2,400 MW), Vineyard Wind 2 (1,200 MW).
Work Order stopped	Revolution Wind [74], Atlantic Shores offshore wind [75].

To address OSW transmission issues on the U.S. West Coast, the Grid Deployment Office and Bureau of Ocean Energy Management (BOEM) jointly published the Action Plan for Offshore Wind Transmission Development in the U.S. West Coast Region in January 2025 [65].

Canada is in a good position to participate in the global offshore wind industry, which is expected to draw $1 trillion in investment by 2040, owing to its longest coastlines of almost 243,000 kilometers [76]. According to a recent report published by [77], research on OSW is being advanced by a group of scientists from Natural Resources Canada (NRCan) in Atlantic Canada in order to use its enormous potential fully.

TABLE 8. Offshore wind farm projects plans in different Canadian Regions with estimated capacity and technology types; Allan Array Floating Wind Farm has the highest capacity of 17 GW, while Sea-Breeze Tech Floating Wind Project has the lowest capacity of 100 MW [79].

Project Name	Estimated Capacity	Technology Type
The Nova East Wind Floating Wind Farm	300 to 400 megawatts (MW)	Floating wind technology.
Sea-Breeze Tech Floating Wind Project	100 MW	Floating turbines, Sensors, and control systems to modify the orientation of the turbines.
Yarmouth Offshore Wind Farm	960 MW	Fixed gravity.
Hecate Offshore Wind Farm [80]	400 MW	Offshore mount unknown
Allan Array Floating Wind Farm	17 GW	Fixed bottom wind farms (10 GW), Floating projects (7 GW).

The Department of Energy and Natural Resources Canada in Nova Scotia has suggested five locations for offshore wind farm development: Sydney Bight, French Bank, Middle Bank, Sable Island Bank, and Western/Emerald Bank [78]. The table 8 below discusses a few offshore wind farm project plans in various locations in Canada [79]:

2) SOUTH AMERICA

According to the Energy Research Office of Brazil (EPE), the Brazilian EEZ has a total offshore wind potential of roughly 1.6 TW, with 700 GW in areas with ocean depths as low as 50 m. The most attractive areas in northeastern Brazil for offshore wind farm installations are the States of Maranhao (MA), Piauí (PI), Ceará (CE), and Rio Grande do Norte (RN), which have a broad continental shelf and ocean depths under 50 meters. In the southern region, notable offshore wind resources are found south of the states of Santa Catarina (SC) and along the Rio Grande do Sul (RS) coastline [81].

With an average wave power of 39 kW/m, the 4200 km Chilean coastline has a total wave power of 165 GW. Additionally, in central Chile, close to the Valparaiso coast, there are nearshore wave energy resources. Southern Chile is home to a significant amount of tidal energy, with the Magallanes Strait in Magallanes Region and Chacao Channel in Los Lagos Region having the most significant tidal energy power in the nation [81].

The offshore winds and thermohaline gradients in the Caribbean, the tides in the Pacific, and the waves in both basins offer a valuable substitute for supplying electricity to the main grid, distributed generation to nearby coastal communities, or micro-grids (autonomous or grid-connected). The richest resource potential is found in the north Caribbean, which includes Atlántico, Magdalena, and La Guajira [81].

3) EUROPE

The adoption of offshore wind energy is essential to guaranteeing the competitiveness and energy security of Europe [82]. Europe now has 291 GW of wind power capacity

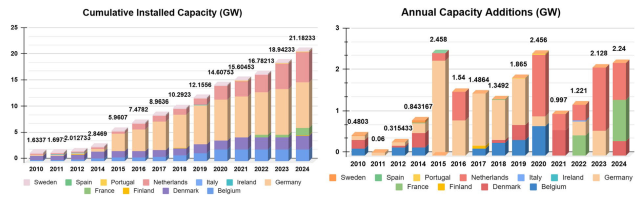


FIGURE 20. Offshore wind energy deployment across major European countries from 2010 to 2024. The total installed offshore wind capacity (GW) on the left shows long-term growth and national contributions, while the annual capacity increases (GW) on the right show year-over-year installations [82].

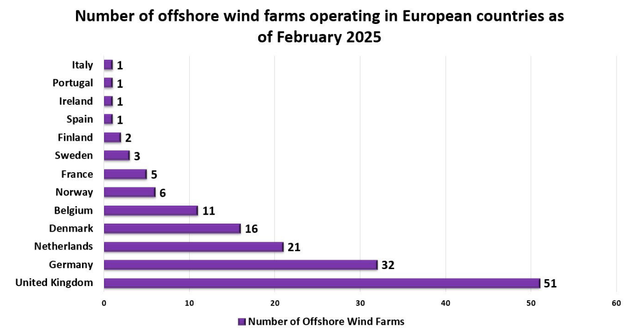


FIGURE 21. Operational offshore wind farms across European countries by the end of February 2025, highlighting the highest number of installations in the United Kingdom (51 farms), followed by Germany (32), the Netherlands (21), and Denmark (16). Medium development is observed in Belgium (11), Norway (6), and France (5), while Sweden (3) and Finland (2) show fewer installations. Spain, Ireland, Portugal, and Italy each have a single operational offshore wind farm, reflecting their relatively early stage of offshore wind development [84].

as of 2025, with 37 GW coming from offshore wind. In order to reach its goal of 425 GW by 2030, the EU is anticipated to construct 22 GW of new wind farms every year between blue 2025 and 2030, bringing its total installed capacity to 344 GW [83]. The cumulative amount was 21.2 GW at the end of 2024, which showed a total increase of 2.2 GW from 2023 [55], [82]. Figure 20 presents the wind energy capacity additions and installed capacity in the EU, spanning from 2010 to 2024.

The number of operating offshore wind farms as of February 2025 across different countries in Europe is shown in the Figure 21 [84].

The table 9 below discusses a few offshore wind farm project plans in several locations in Europe.

4) ASIA

As of June 2024, China had the most offshore wind farms with 129 installations totaling 37.7 GW of installed capacity, which made up over half of the world's total [66], [85]. China has become the world's leading offshore wind powerhouse as of March 2025, having grown from less than 5 GW in 2018 to 42.7 GW in 2025 (50% of worldwide capacity) [86]. The largest offshore wind farm in China is Qingzhou Offshore Wind Farm, which is situated in the sea area close to Shaba Town in Yangxi County, Guangdong Province. With

TABLE 9. Overview of leading offshore wind farm projects in Europe, summarizing the project's capacity, turbine types and numbers, and project location. The table shows both operational and in-development installations and highlights the scale of offshore wind deployment across the region. Dogger Bank Wind Farm, North Sea, Yorkshire Coast, UK has the highest capacity of 5.6 GW while Walney Extension, located in Irish sea, coast of Walney Island, UK has the lowest capacity of 659 MW [85].

Project Name	Capacity (GW/MW)	Number & Types of Turbine	Location
Hornsea 2 Wind Farm: Designed and built by Ørsted; operational in 2022. Produces enough electricity to power almost 1.4 million households	1.4 GW	165 SG 8.0–167 DD offshore wind turbines	North Sea, Yorkshire Coast, UK
Dogger Bank Wind Farm: Under development; expected to produce enough electricity to power almost 6 million homes annually	5.6 GW	277 GE Haliade–X 13 MW turbines	North Sea, Yorkshire Coast, UK
Hollandse Kust Zuid: Largest subsidy-free wind farm in the Netherlands; enough for almost 1.5 million homes	1.5 GW	139 SG 10.0–193 DD turbines	North Sea, west coast of the Netherlands
Borssele Wind Farm: Pilot project using innovative technologies; produces enough electricity for almost 1.5 million households	1.5 GW	94 SG 8.0–167 DD and 79 V164–9.5 MW	North sea, coast of Zeeland, Netherlands
Seagreen Offshore Wind Farm: Scotland's largest wind farm; can power around 1.6 million homes	1075 MW	114 Vestas V164–10 MW	North Sea, coast of Angus, UK
Triton Knoll Offshore: Capable of powering almost 935000 UK households annually	857 MW	90 MHI Vestas V164–9.5 MW	The Wash, coast of Lincolnshire, UK
East Anglia ONE: One of the major wind farm projects of UK; can to power almost 630,000 houses annually	714 MW	90 Siemens SWT-7.0-154 turbines	North sea, coast of Suffolk, UK
Walney Extension: Capable of powering almost 600000 UK homes per year	659 MW	40 MHI Vestas V164-8.0 MW turbines & 47 SWT-7.0-154 7 MW turbines	Irish sea, coast of Walney Island, UK

a combined capacity of 1,000 MW, the wind farm is divided into two phases:

- Qingzhou 1: 400 MW
- Qingzhou 2: 600 MW

It is the first project worldwide to feature a 500 kV HVAC offshore substation paired with a 500 kV three-core subsea cable. It has produced 72.31 million kWh of power since achieving full-capacity grid connectivity in December 2023, and when it is fully operational, it will produce 3.6 TWh of emission-free power annually.

Taiwan is the Asia-Pacific region's largest offshore wind market, second only to China, and it is expanding quickly. At the end of 2023, Taiwan's offshore wind capacity stood at 2.25 GW, and the Taiwanese government aims to expand this capacity by 5.7 GW by the end of 2025 to meet its renewable energy goal [87]. Greater Changhua 1 & 2a is Taiwan's largest offshore wind farm and the country's first major offshore wind power project. It began operations in April 2024, and almost one million households in Taiwan can receive electricity from this wind farm. With a combined capacity of 900 MW, the project consists of two offshore transformer platforms and 111 Siemens Gamesa 8 MW wind turbines [85].

In order to achieve net-zero emissions by 2050, Japan plans to have offshore wind capacity of 10 GW by 2030 and 30-45 GW by 2040, including floating wind [88].

According to The Philippines Offshore Wind Roadmap, which was introduced in April 2022 by the World Bank Group in collaboration with the DOE, the International Finance Corporation, and the Energy Sector Management Assistance Program, the Philippines could install up to 21 GW of offshore wind capacity by 2040. With a total potential capacity of over 65 GW, DOE had authorized 92 offshore wind energy service contracts (WESCs) as of April 2024 [89].

Table 10 shows a few of the offshore wind projects with an electric business license, with a combined planned capacity of 28 GW in South Korea as of 2025 [90].

5) AUSTRALIA

Although the offshore wind energy industry in Australia is still in its early stages, it has the capacity to become a significant part of the nation's transition to renewable energy, alongside onshore wind and solar. It can generate up to 2,000 GW of electricity. Victoria is currently at the forefront of offshore wind policy, and plans to install 2 GW of offshore wind by 2032, 4 GW by 2035, and 9 GW by 2040 [92]. Figure 22 illustrates proposed sites for Australia's offshore wind farm and a few projects across different regions.

Table 11 summarizes the global OSW deployment scenarios.

IV. COMPARATIVE ANALYSIS OF MHK AND OSW TECHNOLOGIES

Although MHK and OSW both function in marine environments, their foundations differ because of engineering factors and resource properties. It is vital that we compare the advantages, disadvantages, and possibilities of marine hydrokinetic (MHK) technologies with offshore wind energy in terms of various factors such as generation capacity, distance from the coastline, structure type, and water depth.

Offshore wind technology selection is greatly influenced by water depth [93]:

TABLE 10. Selected offshore wind projects in South Korea as of 2025, showing each project's installed capacity (MW), development status (operational, under construction, or in development), and the ownership. The table includes both earlier utility-scale installations and recently tender-awarded projects that have entered the national offshore wind development pipeline [90], [91].

Project Name	Capacity (MW)	Status	Ownership / Developer
Gunsan Port	3.0	Operational	KEPCO
Yeonggwang Yaksu	4.3	Operational	Jeonnam Development Corporation (JNDC).
Woljeong	5.0	Operational	Korea Institute of Energy Research (KIER).
Southwest Phase 1	60.0	Operational	Korea Hydro and Nuclear Power (KHNP); Korea East–West Power (EWP); Korea South-East Power (KOEN); Korea Southern Power (KOSPO); Korea Western Power (KOWEPO); Korea Midland Power (KOMIPO); Korea Offshore Wind Power (KOWP); KEPCO.
Yeonggwang Gun	34.5	Operational	EWP; Daehan Green Power; Unison.
Tamra	30.0	Operational	Doosan Enerbility Co., Ltd.; NongHyup Bank; KOEN.
Jeonnam 1, 2 and 3	897	Phase 1: 2022 auction award; in construction Phases 2–3: Development	SK E&S; Copenhagen Infrastructure Partners.
Halim	100	Construction	KEPCO; Hyundai Engineering & Construction; KB Kookmin Bank; Baram Corp.; KOMIPO.
Anma	532	Development	JNDC; Korea Wind Corporation Co., Ltd.; KHNP; Hyundai Engineering and Construction; Equis Development Pte. Ltd.
Yeonggwang Chilsan	151.2	Development	EWP; Daehan Green Power; Unison; CW NR Co. Ltd.
Ulsan City	6100	Development	Ulsan City in collaboration with state-owned enterprises and commercial developers.
Gray Whale (floating)	1500	Development	Corio Generation; TotalEnergies; SK Ecoplant.
Southwest Offshore Wind Power Demonstration Complex	400 MW	Development	KEPCO's Korea Offshore Wind Power.
Handong-Pyeongdae Offshore Wind Power project	100	Development	Dongseo Power.
Dadaepo Offshore Wind Power project	99	Development	Corio Generation; TotalEnergies; SK Ecoplant.
Aphae Offshore Wind Power project	80	Development	Korea Electric Power Technology-led consortium.

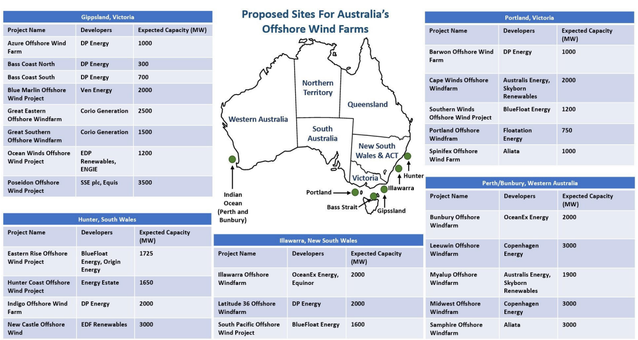


FIGURE 22. Map and summary of proposed offshore wind farm sites in Australia, indicating project locations across Gippsland, Portland, Hunter, Illawarra, and Perth/Bunbury, along with their respective developers and expected generation capacities [92].

- **Shallow-water sites (< 30 m):** Usually use proven fixed-bottom monopile or gravity-based foundations.
- **Transitional waters (30–60 m):** Usually require jacket or lattice structures anchored to the seabed, even though commercially deployed but less common.
- **Deep-water environments (> 60 m)**: Fixed-bottom foundations become impractical in this water depth and floating platforms, such as spar-buoy, semi-submersible, or tension-leg designs, are used; still in the demonstration or early commercial phase.

Offshore wind potential grows gradually as the farms move farther from shore and into deeper waters, with far-shore deepwater sites providing the most significant contribution globally; 257,081 TWh/year compared to only 35,875 TWh/year near-shore shallow sites. The regions with the highest overall potential are North America with 104,901 TWh/year, followed by Eurasia, the combined continental landmass of Europe and Asia with 85,462 TWh/year, and Asia Pacific with 76,757 TWh/year [94].

According to the report by [95], the 200-m depth employed on the US West Coast to determine the upper bound of theoretical resource is a suitable depth for future systems in terms of wave energy. However, due to non-technical reasons, the initial wave energy converter (WEC) device generations will probably be installed in shallower ocean depths of 50–100 m. The theoretical wave resource data were reanalyzed at a 100 m sea depth in order to ascertain the technological and practical resources in the near future. Based on the analysis's findings, the theoretical wave energy resource in the US at a depth of 100 meters is 1851 TWh/year. The ratio of water depth to turbine diameter is important for future tidal arrays and must be appropriately taken into consideration in numerical models to yield accurate results, according to a study by [96]. Most research to date has focused on shoreline oscillating water columns (OWCs) and offshore floating devices. OWCs are valued for their simple operation: waves drive air through a self-rectifying turbine, and for their easy onshore access. Offshore floating systems are favored for harnessing the higher average wave power in deep water and facing fewer topographical limits. In contrast, seabed-mounted near-shore devices with 10–20 m depth and 0.5–2 km from shore have received less attention,

TABLE 11. Comparative overview of global offshore wind energy deployment scenarios. Table highlights the prominent OSW technologies, technical potential, main advantages, and deployment status across various countries in the world; Europe leads in large-scale deployment, while other countries are experiencing rapid expansion across multiple deployment stages.

Region	Prominent Technology	Technical Potential	Number of Operating Projects	Deployment Status
North America (United States, Canada)	Fixed-bottom wind farms, floating turbines, fixed gravity	High	4 operating projects in the United States	A wide range of projects are in the development stage and being tested in research facilities
South America (Brazil, Chile, Colombia)	Fixed bottom, floating wind	High	No large-scale operating projects	Research and early prototype testing stage
Europe	Offshore wind turbines	High	51 projects in the United Kingdom, 32 in Germany, 21 in the Netherlands,16 in Denmark, 11 in Belgium	Multiple operational scale projects
Asia (China, Taiwan, Japan, Philippines, South Korea)	Fixed-bottom, floating offshore, offshore transformer platform	Medium to high	129 offshore wind farm installations in China, 1 operating farm in Taiwan, 6 operational projects in South Korea	Multiple projects in planning, testing, construction, development, and operational stages
Australia	Fixed-bottom, monopile foundation	Medium	No large-scale operational farms	Multiple projects in the proposed and development phase

mainly because of their slightly lower wave power potential; typically only 5–10% less than deep water sites. However, there are several possible benefits that near-shore devices have over offshore ones. In addition to having reduced power losses in the cable, a near-shore device will be less expensive to install than an offshore one due to its proximity to the coast. The lower sea level and closer proximity to the shoreline are also expected to cut installation and maintenance costs because activities may be carried out with less specialized equipment and during shorter weather periods [97].

Water depth is a vital consideration when deciding on the type and viability of offshore wind energy and marine hydrokinetic energy installations, and Table 12 summarizes the relationship between water depth and the corresponding technology types for both offshore wind energy and marine hydrokinetic; wave and tidal applications.

A report published by [103] discusses ultradeep water, defined as depths between 1300 m and 3000 m, and the commercial projects being deployed in that depth because of the significant potential for wind energy generation in deeper water for some locations. However, for ultradeep deployment, depth sensitivity is an important factor to consider as it varies across offshore wind components and is a critical driver of foundation type selection. Table 13 shows the sensitivity to ultradeep water depth for different offshore wind components.

Wave energy converters can increase offshore wind projects' capacity factors without appreciably raising costs by sharing balance-of-system infrastructure [104]. It is possible to install wave farms between the towers of offshore wind farms, to capture power from both wind and waves [105]. Furthermore, ocean industries that usually operate far from conventional power sources could benefit from increased energy reliability if marine energy technology were used to power offshore operations like aquaculture farms or ocean observation equipment [106]. Figure 23 compares the percentage breakdown of key project components for wave, tidal, and offshore wind energy systems, highlighting overlapping areas, synergies, and technology-specific elements.

TABLE 12. Relationship between water depth and technology type for OSW and MHK applications, indicating in which depth each technology is typically feasible, N/A indicates information not available.

Water Depth	Offshore Wind Energy [98]	Marine Hydrokinetic Energy	
		Wave	Tidal
< 5 m	N/A	Too shallow for deployment	Too shallow for deployment [99]
(8–26) m	N/A	WaveRoller [100], WET-NZ (1/2 scale) StingRAY WEC [101]	Tidal, river, and ocean technologies [101]
(26–30) m	Suction buckets, Gravity foundations	N/A	Marine floating and fixed structures [81]
40 m	Tri-piles	N/A	N/A
50 m	Tripods	Usual wave technology deployment range [101]	Usual tidal turbine deployment range [96]
60 m	Jackets	N/A	N/A
70 m	N/A	HINMREC—Wave and OTEC Test Facility [102]	N/A
100 m	Jack-up	N/A	N/A
220 m	Floating	N/A	Too deep for economical tidal energy [98]

V. TECHNICAL CHALLENGES IN MARINE HYDROKINETIC ENERGY AND OFFSHORE WIND ENERGY DEPLOYMENT

The technical difficulties that determine whether MHK and OSW can function reliably, connect seamlessly with current grids, and extend beyond pilot deployments are what limit their large-scale deployment, rather than the availability of resources.

Table 14 summarizes the key technical challenge areas and their associated priority topics; however, the following

TABLE 13. Overview of offshore wind components sensitivity to ultradeep water depth; while Wind Turbine, Floating Platform, and Offshore Substation show low sensitivity to ultradeep water depth, Mooring Line, Anchor, Static Power Cable, and Dynamic Power Cable demonstrate high sensitivity [103].

Component	Sensitivity to Ultradeep Water Depth
Wind Turbine	Low
Floating Platform	Low
Offshore Substation	Low
Mooring Line	High: mooring line length and configuration increase with depth
Anchor	Medium: anchor type selection is usually depth dependent.
Static Power Cable	High: cable length, insulation requirements, and installation are influenced by water depth.
Dynamic Power Cable	High: cable specifications are depth dependent, and cable length generally increases with water depth unless it is fully suspended.

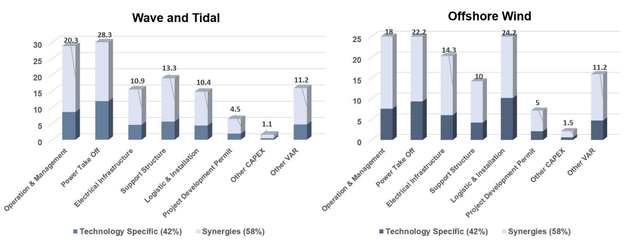


FIGURE 23. Synergies between wave and tidal energy (Left) and offshore wind (right). Each bar separates technology-specific costs (42%) from shared or synergistic costs (58%), including operations and maintenance, power take-off systems, electrical infrastructure, support structures, logistics and installation, and project development expenses [45].

TABLE 14. Challenge areas and priority topics for ocean energy development. Major technical and system-level issues involving ocean energy farms, next-generation technologies, modeling and analysis tools, and supporting technologies are presented in the table, along with the main issues identified to resolve these issues to promote broad adoption [107].

Challenge Areas	Priority Topics
Design and validation of ocean energy farms	i. Demonstration of pilot farms ii. Demonstration of single devices iii. Design and validation of other ocean energy technologies
Next generation of technologies and subsystems	i.Disruptive wave energy devices ii. Innovative PTO and control systems iii. Advanced moorings, foundations, and power connections
Ocean energy analysis and modelling tools	i. Advanced simulation of ocean energy subsystems and devices ii. Analysis and planning tools for ocean energy farm deployment iii. Modelling and simulation of farm construction and operation
Integration of enabling technologies	i. Innovative materials and manufacturing processes ii. Application of latest instrumentation and sensor technology iii. Use of artificial intelligence and big data

subsections delve deeper into the significant technical issues that impact the widespread use of MHK and OSW technologies.

A. RESOURCE ASSESSMENT AND CHARACTERIZATION

The development of wave energy depends on accurate resource characterization, and several wave models and techniques are employed globally for this purpose. To accurately and consistently characterize wave resources, it is imperative to understand the state of science, identify knowledge gaps, and suggest best practices [108]. For tidal current energy, a deeper understanding of energy dissipation in turbine wakes and the resulting increase in drag is required to improve the understanding of the tidal energy technology resource. With more information, it will be possible to model turbine arrays in order to identify the optimal energy extraction scenarios [33]. When it comes to OSW, the ability to measure and evaluate available wind resources is essential to the development, siting, and operation of a wind energy plant. When planning a new wind power plant, developers rely on location-specific data regarding wind speed, weather patterns, terrain, and other factors to inform siting and design decisions [109].

B. GRID INTEGRATION AND POWER QUALITY ISSUES

Grid-connected power quality issues of offshore wind power are becoming a more significant issue because of the intermittency of wind energy, the unpredictable performance of offshore wind turbines, the high percentage of renewable energy integration in the grid, and the usage of power electronic devices. These factors negatively affect the power system's stability and can even result in serious safety incidents [110]. Similarly, the power quality of a local electrical network may be negatively impacted by the natural variations of wave and tidal energy. Significant problems with dynamic device modeling were found in the wind energy sector, including model incompatibility, low dynamic model quality, and model numerical instability. These issues are regarded as a significant obstacle to the further grid integration of marine energy converters, given the wide variety of device types in the emerging ocean energy sector. An additional challenge to connecting ocean energy devices to the grid is that current grid codes, which were primarily created for wind energy, may not be suitable or helpful for ocean energy devices [111]. Moreover, there is a lack of robust, validated models that undermines confidence in grid integration studies and impedes the development of advanced hybrid energy system architectures such as virtual power plants and full hybrid systems, and advancing them is essential for ensuring reliable and efficient deployment of MHK and OSW hybrid systems [112].

C. TECHNOLOGY MATURITY

The ocean energy sector has a wide range of technology solutions, but limited data availability, which makes it harder to recognize high-performance designs with high reliability and identify promising technologies [95]. Testing and demonstrating prototypes in realistic conditions to validate their performance and durability is still one of the significant challenges in this sector. It is also important to design efficient approaches for installation, grid integration, operations, and maintenance, as well as to run R&D for innovative systems and components. Furthermore, focusing on tool development to optimize device performance and reliability can significantly help in advancing the technologies in this field [108].

D. OPERATION AND MAINTENANCE

There are many operational challenges due to the inherent difficulties of maintaining turbines that are miles offshore. Conventional maintenance techniques, which mostly rely on crewed vessels, diving operations, and manual inspections, result in longer downtime, increased operating costs, and eventually affect the reliability and energy production of wind farms. Maintenance procedures are starting to change as a result of new smart technologies, including artificial intelligence (AI), remotely operated vehicles (ROVs), and real-time monitoring systems. They provide feasible solutions to streamline maintenance processes and assist the sustainable growth of offshore wind energy globally by increasing operational safety and efficiency [113].

E. DEPLOYMENT AND DEMONSTRATION

Test facilities and authorized demonstration sites are usually unavailable to developers who are prepared to test full-scale prototypes, which makes it more difficult for them to perform tests, improve installation and operation, as well as validate device performance in its intended resources [95]. Accurately assessing the value of marine energy using conventional measures, such as the cost of energy produced, is challenging due to its lack of practical deployment and its high costs compared to wind and solar power. Developers and utilities are likely to be reluctant to implement maritime energy devices in the absence of these data [7].

Furthermore, hybridization of MHK with OSW poses a few more challenges, such as [114]:

- Compared to offshore wind turbines, which have a capacity of 10-15 MW per unit, WECs have a comparatively smaller power production of 0.1-0.5 MW per unit.
- The incorporation of WEC into offshore wind designs may result in adverse impacts, such as increased pitching motions, mooring, and tower loads.
- The possibility of collision on WECs will significantly rise due to the addition of complexity, such as the need to "beef up" relevant connection structure components on the hull and implement synchronization controls.

VI. GRID INTEGRATION AND SERVICES

A. CO-LOCATION STRATEGIES AND SHARED INFRASTRUCTURE

Co-location is the process of integrating various technology types using a single grid connection point or establishing several generation projects, including energy storage [115]. Additionally, it can refer to the temporal and/or spatial overlap of several industries that are moderately connected. [116]. By sharing installations, it is possible to make better use of the marine resource, lower installation and operating costs, improve energy resource predictability, achieve smoother power output, or extend weather windows for maintenance and operation activities. Figure 24 presents different types of combined wave-wind technologies.

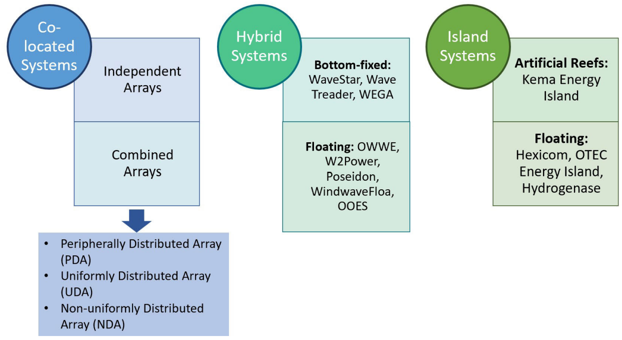


FIGURE 24. Classification of various marine renewable configurations: co-located systems are either independent or combined; arranged as PDA/UDA/NDA, hybrid systems are bottom-fixed or floating, and island systems are artificial-reef and floating islands [6].

Marine renewable energy, for example, wave and tidal, has the potential for large-scale deployment, and it has been suggested that deploying several marine energy technologies at the exact location is a method of minimizing the individual operation cost [117]. They have favorable co-location potential, improved consistency, and minimal visual impact in power generation compared to other renewable sources. It can be integrated with battery storage system or solar generation to meet the power demand for surface-level sensors. Furthermore, MHK systems offer distinct advantages, such as effective co-location with sensors, markers, subsea inspection vehicles, and shared infrastructure, as well as continuous power generation and enhanced stealth characteristics [118].

In the context of offshore wind, co-locating multiple technologies together aims to minimize volume and revenue risk for generators while optimizing the value of shared resources such as access, grid connection, and land and marine infrastructure [115]. According to research conducted in the North Sea, multi-use platforms' operating and maintenance expenses might be lowered by 10% as a result of shared vessel use and repair activities [119]. Current case studies in Western Australia and the United Kingdom are investigating the use of fixed foundation wind farms as aquaculture feed barges and offshore renewable energy and hybrid platforms as a way to supply the energy demands of aquaculture operations [120]. To better understand the practical implementation of co-location, three key configurations have been identified, each with distinct infrastructure and operational characteristics [115].

i. **Offshore wind co-location with flexibility (on land):**

- Behind the connection point.

- The onshore substation receives electricity from the offshore wind farm.
- Optimized grid connection utilization because offshore wind landing sites typically have limited grid connections.
- Preserves as much of the land envelope as possible for the onshore substation (connection point).

ii. **Offshore wind co-location with flexibility (at sea):**

- Behind the meter.
- An offtaker offshore (emission-free hydrogen production or fresh demand) or an electricity storage asset receives and uses electricity.
- The offshore wind farm is connected to the mainland by high-voltage wires, and the hydrogen generated can be shipped by pipeline or ship.

iii. **Off grid co-location:**

- Centralised offshore emission-free hydrogen production (offshore platform).
- An offshore wind farm is connected to an electrolyser situated on an offshore platform.
- Optimizing offshore wind production during curtailment periods.
- Increased adaptability to power hydrogen or storage during low-demand (low-price) times or supply energy during high-demand (and high-price) times.

However, the advantages and impacts of integrating wave and wind energy systems vary significantly on the basis of regional weather and metocean conditions [121]. A study evaluating combined wind and wave resources along the coasts of Latin America and Europe found that European sites performed better in winter [122]. In contrast, Latin American sites offered more consistent potential throughout the year. Along China's southeast coast, although the ideal sites for wind and wave energy differ, their combined use has been shown to reduce energy output variability and enhance annual generation [123].

Another aspect to take into consideration for co-located farms is wake effect. The phenomenon known as the wake effect describes how turbines produce a trail of slower, more turbulent air after the wind has passed them. This track can extend a considerable distance and is known as a wake and has an impact not just on the turbine itself but also on other nearby turbines, which will generate less electricity due to lower incoming wind speeds. Additionally, turbulent airflow reduces the efficiency of turbines by creating mechanical stress, which may increase wear and tear and maintenance requirements. Wake loss is the term for the decrease in energy production brought on by the wake effect [124]. Currently, CFD (Computational Fluid Dynamics) numerical simulation, engineering wake mode, roughness length-based model, and wake superposition model are used in the study of offshore wind turbine wake effect [125]. A CFD wind turbine wake-ground interaction model in wind farms was proposed and used in both flat and complex configurations in a study conducted by [126]. Even in the close wake region, the hybrid approach (CFD-actuator disk model) has produced good wake results.

Table 15 discusses hybrid and co-location strategies, their advantages as well as limitations for MHK and OSW technologies.

It is anticipated that co-locating wind and wave energy technologies will have synergistic effects that lower development costs both directly and indirectly. There is currently no cost model that takes into account all of these consequences, and while some of these effects have been quantified, many have not been connected to cost. Furthermore, floating offshore wind platforms may offer access to abundant resources farther offshore in regions where fixed-bottom offshore wind projects are impractical. In a study by [131], the authors identified research gaps and uncertainties to be reduced in future work and created a cost model that depicts co-located array advances, specifically for floating offshore wind and wave energy converter technologies. These co-located energy farms can realize the synergies between the two renewable energy sources, thereby addressing some of the issues related to offshore wind generation. Among these, [10] concentrated on the lengthier non-operational periods of offshore wind turbines compared to their onshore counterparts, which are usually brought on by maintenance delays because of the challenging marine circumstances. Co-located wave energy converters would create a shielding effect over the wind farm by acting as a barrier to harvest energy from the waves. Based on this, the authors sought to conduct a comprehensive analysis of the economics of wave energy as well as the synergies between wave and offshore wind energy, with a particular emphasis on the shadow effect and the consequent improvement in wind turbine accessibility.

B. REACTIVE POWER SUPPORT IN COASTAL GRID CONTEXT

As coastal regions integrate more renewable generation such as offshore wind, marine hydrokinetic (MHK) systems, and other variable resources, maintaining adequate reactive power support becomes critical for grid stability. Table 16 presents some challenges for renewable energy sources in comparison to traditional plants, highlighting that while renewables can provide reactive power, a few issues make this support less dependable [132]. For example, renewable energy sources are not directly connected to the grid; they do not instantly contribute kinetic energy or rotational inertia. As a result, in order to maintain voltage stability, reduced inertia from these sources demands more active and responsive reactive power compensation [133].

Marine hydrokinetic (MHK) energy's reactive power support is crucial for maintaining the electrical grid's stability, particularly given the erratic and variable nature of ocean currents and waves. In order to maintain grid voltage and lessen power quality problems like voltage flicker, MHK devices regulate their reactive power output using power electronics and sophisticated control systems.

TABLE 15. Summary of different co-location and hybrid MHK and OSW technologies. The table outlines the system configuration for each strategy, as well as the main advantages for each strategy that make them intriguing, and the main existing limitations that hinder large-scale deployment.

Integration Strategy	Description	Advantages	Limitations
Co-located offshore wind turbines and wave energy converters, California [127]	The power performance and variability of offshore wind and wave energy farms in California were modeled in this study using the National Data Buoy Center's extensive dataset of 143 yearly records of hourly offshore wind and wave measurements.	• Wave farms would have capacity factors of 22% to 29%, while offshore wind farms would have capacity factors of 30% to 50%, showing moderate-to-high capacity factors. • The aggregate power from a co-located wind and wave farm achieves reductions in variability • In contrast to over 1000 hours for offshore wind or over 200 hours for wave farms alone, combined farms in California would have less than 100 hours of no electricity output annually.	This study investigates the synergistic potential of co-locating the two marine renewables in California. Since their low temporal correlations result in low variable aggregate power, direct competitive comparisons of wind and wave power performance should be avoided, and definitive conclusions cannot be drawn from these results.
Power Co-Generation from Hybrid Offshore Wind and Wave Energy [128]	This study presented co-located systems by combining the OWT with a WEC array as a simple option for advancing HOWWE technologies at the present stage, and it emphasized power conversion and the implementation of advanced control coupling in Hybrid offshore wind and wave energy (HOWWE) systems.	• For the PMSG and linear generator, respectively, HOWWE can maximize power using various control strategies. • Additionally, the power output can be adjusted using various power conversion systems, such as VSC and VSI with HVDC transmission.	To harness electricity from the integrated HOWWE system, several power-conversion architectures must be carefully selected and coordinated. Additionally, significant research is needed in control design, efficient power conversion, and reliable grid integration.
Microgrid Using Tidal and Wind Energy, Cook Strait [129]	This study evaluated a DC-linked wind-tidal battery-based microgrid for electricity generation in node CPK0331 (Central Park) in the southern region of New Zealand's northern islands. They considered the region's strong wind and tidal resource potential to design a microgrid that would connect to the national grid at an affordable cost.	• An offshore location near CPK0331 (known as the Central Park) has sufficient tidal currents to produce power for 69.3% of the year. • Additionally, the wind speed at the Foveaux site is sufficient to produce electricity for 78.2% of the year.	The system cannot supply continuous renewable power throughout the year, requiring energy storage and grid interconnection.
Offshore Hydrogen Integration [130]	Electrolyzers at Offshore wind farms are able to split water into hydrogen and oxygen using the generated electricity, with technologies such as alkaline, proton exchange membrane (PEM), or solid oxide systems.	Hydrogen is a reliable energy storage medium and can store extra electrons from renewable energy sources in molecular form, furthermore, helping stabilize power grids that depend on sporadic sources like solar and wind.	Hydrogen's extremely flammable nature demands strict safety protocols for handling, storage, and transportation during the offshore manufacturing process, which adds complexity.
Hybrid AC-DC/DC-DC Conversion Systems in Smart Microgrids [12]	This paper used advanced control strategies and modeling techniques to evaluate the effectiveness of integrating offshore wind farms into smart microgrid systems by investigating hybrid conversion systems that incorporate both AC-DC and DC-DC technologies and multi-terminal configurations.	High load-following capabilities have been shown by the multi-terminal DC-DC converter control schemes, which have effectively managed dynamic load profiles while preserving steady voltage levels with little ripple.	The multi-stage power conversion, complex control methods, and coordinated protection schemes raise system complexity and could make large-scale deployment, cost optimization, and operational scalability difficult.

For OSW plants, a comprehensive design is necessary, including wind turbine generator (WTG) reactive power capability, equipment voltage and current limitations, and cable charging reactive power during the energizing process. This ensures developers meet the reactive power capability requirements and guarantee dependable operation. In addition to WTG's inherent PQ capacity, reactive power compensation is typically accomplished via a variety of reactive power compensation equipment, including STATCOM and (fixed/variable) shunt reactors. Most grid codes describe three control modes [134],

i. Reactive power control mode,
ii. Power factor control mode, and
iii. Voltage control mode, about reactive power controllability.

The capacity of the Offshore Wind Power Plant (OWPP) to directly regulate reactive power through the reception of external set points in reactive power and power factor control modes, or indirectly through the use of a voltage reference and a predetermined V-Q slope in voltage control mode, is necessary for reactive power controllability [134].

TABLE 16. **Comparison of challenges associated with reactive power support in renewable versus traditional energy sources. The table shows challenges related to real and reactive power, highlighting issues such as grid inertia, dynamic response, intermittency, voltage and frequency regulation, and capital and operational costs [132].**

Challenges	Renewable Energy Sources		Traditional Energy Sources	
Power Components	Real Power, P	Reactive Power, Q	Real Power, P	Reactive Power, Q
Intermittency	Yes	Yes	No	No
Voltage and Frequency Control	Moderate	Yes	No	No
Grid Inertia	Yes	Yes	No	No
Dynamic Response	Yes	Yes	No	No
Capital and Operational Costs	Yes	Yes	Yes	Yes

C. CONTROL, MODELING, AND SIMULATION APPROACHES

1) MODELING FRAMEWORKS FOR MARINE ENERGY MICROGRIDS

A case study conducted in [135] presents a thorough framework that encompasses a wide range of planning issues for studying ME microgrids, which includes establishing preliminary plans for community involvement, modeling the Marine Energy microgrid, and assessing its long-term feasibility and techno-economic performance. This report proposed a microgrid planning approach that placed community engagement at the forefront of feasibility assessment. The objective was to identify an optimal energy mix that balances cost efficiency, local energy adoption, and system resilience. Two primary simulation tools have been utilized in this case study:

- **Xendee platform:** for modeling and optimizing energy scenarios, and
- **PowerFactory:** for assessing new generation technologies and their compatibility with existing infrastructure.

St. George, Alaska, was selected as a representative site due to its diesel dependency, well-characterized wave energy resource, and existing fishing-based economy. This framework and toolkit will eventually provide interested communities with technical support to help them deploy and gain the benefits of microgrid solutions. Figure 25 illustrates the proposed Community-informed pre-deployment feasibility analysis framework.

The study demonstrated that early-stage planning that incorporates both techno-economic modeling and community priorities can significantly enhance the resilience and adoption rate of marine microgrid systems.

2) PERFORMANCE EVALUATION OF REACTIVE BLADE TIDAL TURBINE

The report published by [136] presents a novel reactive, reversible blade system made up of several blades that may rotate about their span axis. The reactive blade system reduces drag as the blades rotate, allowing increased rotational speed and power output even in slow currents. Creek Tides (CT) has built a turbine prototype with five reactive blades, which was tested in the recirculating flume of Florida Atlantic University's (FAU) Hydrodynamics Laboratory at different flow rates, both with and without a mechanical load. In these tests, the rotational speed was measured in relation to the incoming flow speed, power efficiency was calculated as a function of flow speed, and torque was measured as a function of incoming flow speed. The highest efficiency of the turbine is around 18% when the Vtip/U is at 0.4. The efficiency exhibits a common pattern across the various scenarios, with an abrupt rise in efficiency followed by a decline when Vtip/U rises.

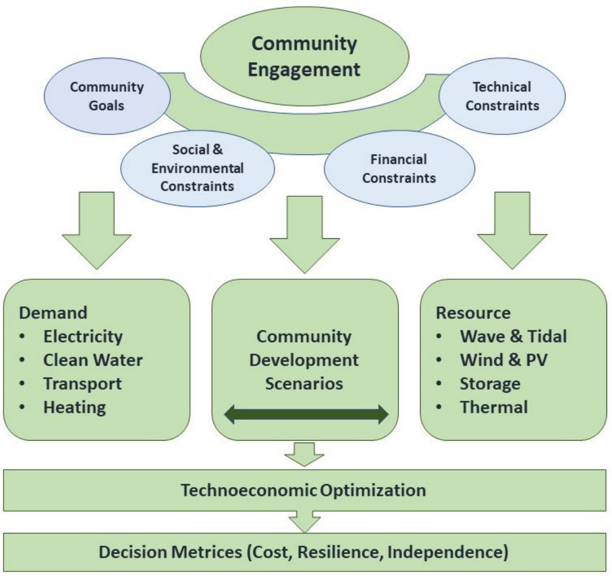


FIGURE 25. **Community-driven pre-deployment feasibility analysis frameworks for studying marine energy microgrids. The diagram shows how local demand profiles and available energy supplies are shaped by community engagement, which is influenced by social, environmental, technological, and economic restrictions. These inputs are evaluated through community development scenarios and technoeconomic optimization to support decision-making based on cost, resilience, and energy independence [135].**

3) WAVE ENERGY POWER SMOOTHING VIA SUPER CAPACITORS DESIGN COMPARISON

The authors in [137] proposed a project with two onboard super capacitor storage system ideas being validated and optimized, and selecting the best Wave Energy Converter design. It provided a comparative analysis of two wave energy converter (WEC) energy storage configurations, emphasizing peak-to-average power ratio (PAPR) performance and overall system cost.

- Design 1 uses a DC-DC converter to regulate the energy stored in the SC and the DC bus voltage.
- Design 2, which is OPI's Triton-C WEC's current design, has the SC directly connected to the DC bus.

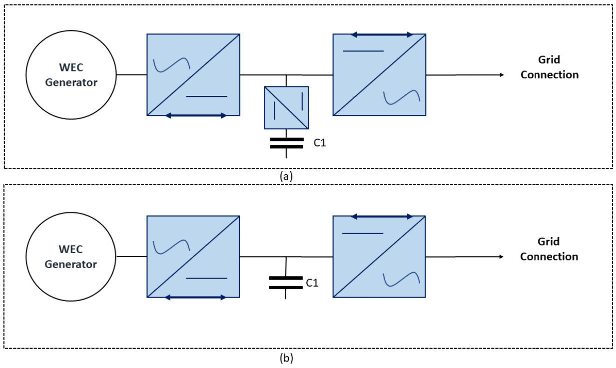


FIGURE 26. Electrical system one line for fixed bus operation with (a) Design 1: employing a DC–DC converter to regulate both the energy stored in the super capacitor (SC) and the DC bus voltage, and (b) Design 2: corresponding to the current Triton-C WEC design developed by OPI, directly connects the super capacitor to the DC bus without intermediate DC–DC conversion. Both configurations illustrate the power-conditioning stages between the WEC generator and the grid connection [137].

The Electrical system, one line for fixed bus operation with both design 1 and design 2, is shown in Figure 26.

The expense of a DC-DC converter exceeds the savings in SC size, even if using one can lead to a greater utilization of the SC energy capacity. The analysis also finds that Design 2 has a higher overall system efficiency.

4) MODELING AND DEPLOYMENT OF MOORING LINES

France Energies Marines [138] has undertaken a structured, multi-phase research initiative to advance the understanding and deployment of synthetic mooring lines, especially those based on nylon for floating offshore wind applications. Starting the period from 2017 to 2026, the initiative consists of three sequential R&D projects:

i) Polyamoor (2017–2020) developed nylon cable configurations and visco-elasto-plastic models fitted for floating wind farms, and introduced an accelerated self-heating method for fatigue prediction. This project developed and validated a nonlinear mechanical model for nylon mooring lines by integrating laboratory testing with real-time sea monitoring using instrumented buoys.

ii) Monamoor (2020–2023) improved these models through 3D finite element analysis, lab creep tests, and sensor-integrated transducers, validated in sea trials.

iii) Bamos (2023–2026) validated a meso-scale model for different construction patterns, extended fatigue life predictions, and advanced degradation modeling using a self-heating fatigue criterion.

Findings showed a strong agreement between sensor readings and model predictions, which indicates that the model is appropriate for precise estimation of dynamic tension and elongation in offshore settings.

5) FLOWATT PILOT FARM PROJECT

The FloWatt project reported in [139], which is located 3 km off the coast of Normandy at Le Raz Blanchard, will deploy six 2.8 MW tidal turbines to achieve a total capacity of 17 MW within a 0.28 km^2 concession. The project is expected to begin construction at the start of 2026 and is anticipated to generate 41 GWh annually, while also supplying electricity to approximately 20,000 residents by late 2028. The design features a 180T tripod equipped with six 330T cast-iron counterweights, with a 24 $\times$ 21 meters distance between pins. A sliding verification will be conducted using geophysical, video, and geotechnical surveys, followed by numerical simulations assessing the effects of gravel and bedrock layers. Gravity-based foundations have been used for small-scale deployments because of their ease and speed of installation, which typically takes roughly three weeks for six foundations with counterweights. The offshore grid connection strategy for the six-turbine FloWatt array features a 10 kV system with wet-mate connectors arranged in three circuits.

6) SUBMERGED WAVE ENERGY DEVICES AND ADAPTIVE MOORING TECHNOLOGIES

Carnegie [140], a global leader in ocean energy technology, has pioneered two leading technologies:

- **CETO:** A wave energy device that uses three integrated Power Take-Off (PTO) units inside a fully submerged buoy to harness the kinetic energy of ocean waves. While artificial intelligence enables real-time adaptation to each incoming wave, allowing for maximum energy extraction, its subsurface functioning minimizes visual impact and provides protection against high wave forces.
- **MoorPower:** A platform that enables offshore applications, such as defense surveillance and aquaculture, which require foundation systems that can withstand inclined loading, approximately 4 million cycles annually, with stress ratios close to zero. Despite their effectiveness, the initial installations utilized monopile foundations, which presented challenges related to cost, limited water depth, and geotechnical risks

Alternative anchoring options, such as rock anchors and helical piles, which offer advantages like removability, reduced seabed disturbance, PTO module hot swap, and easier deployment by smaller vessels, are gaining preference due to recent developments.

7) HARDWARE IN THE LOOP SIMULATION OF OCEAN TURBINES FOR GRID INTEGRATION

The HIL simulation of an ocean current turbine using the OPAL-RT simulator with a 2 HP dynamometer in the loop was presented by the authors in [141]. The objective of the experiment was to verify that the HIL setup labored by monitoring the dynamometer's feedback performance under realistic ocean current conditions with progressively turbulent water velocities. Afterwards, it was scaled and coupled with blade pitch control for Region 3 operation, and was embedded within a microgrid simulation environment. By maintaining a balance between supply and demand, it effectively regulated power output in Region 3. Region

3 is a critical operating range in wind and ocean current turbine control systems, where the turbine actively limits its power production to prevent damage and ensure stability. The microgrid demonstrated good power and frequency performance, indicating that ocean current turbines are viable for real-world applications.

8) THE PLAT-I (PLATFORM FOR INSHORE ENERGY)

The PLAT-I (PLATform for Inshore energy), a tidal energy converter that is situated at the Grand Passage in Nova Scotia. It is equipped with four SCHOTTEL Hydro SIT250 tidal turbines. It was designed using scale model testing at the University of Edinburgh's FloWave test tank and numerical modeling. Low resistance and improved longitudinal and lateral stability are provided by its trimaran design [142]. Alignment with river or tide flow in any direction is made possible by the mooring turret that is incorporated into Sustainable Marine Energy's (SME's) unique design. The SCHOTTEL turbines' low mass and industry-first swing-up turbine deployment modules (SDMs) enable blade and nacelle replacement on-site and provide access to the turbines above the water's surface. In regions such as Asia and South America, where tidal and runoff energy can directly compete with traditional and local electricity generation methods, the device has been created to access protected, lower-resource areas.

9) RivGen POWER SYSTEM

The RivGen Power System utilizes river currents to generate emission-free electricity, thereby drastically reducing the need for fuel [37]. It integrates seamlessly with current networks through smart grid technologies. The longest-running Rivgen Power System project in America is located in the Village of Igiugig, Alaska, as mentioned in section II-B1. In 2023, the Municipality of Chile Chico in Chile signed a contract with ORPC to install a RivGen Power System near the intersection of Generalarrera Lake and Bertrand Lake, as specified in Section II-B2. Figure 27 shows the specifications and features of the RivGen Power System.

10) ATTENTION-ConvNet NETWORK FOR OCEAN-FRONT PREDICTION

By incorporating the hierarchical attention mechanism (HAM), Spatial ConvNet, and a complex hierarchical branching convolutional network (HBCNet) into the network, [143] provided a comprehensive approach to ocean-front prediction. To improve its capacity to capture spatiotemporal information, the network specifically employs a concatenated Spatial ConvNet and HBCNet. The prediction network's attention mechanism, in particular, a relation-aware mechanism that integrates pairwise correlations between ConvNet predictions and projected ocean-front time-series, is a noteworthy feature. The suggested network provided improved prediction accuracy across the Bohai and Kuroshio ocean-front datasets, according to evaluation studies versus SVR, LSTM, ConvLSTM, GAT, and CFCC-LSTM.

Specifications	
Rated power output	40 kW at 2.25 m/s 80 kW at 3.5 m/s
Max. operational water velocity	3.5 m/s
Total turbine capture area (two turbines)	18.0 m^2 (194 ft^2)
Planned maintenance interval	Annual
Major planned maintenance interval	5 year
Length	15.7 m (51.5 ft)
Width	14.3 m (46.9 ft)
Assembled (dry) weight	29,500 kg (32.5 tons)

The reliable power generation from ORPC's RivGen Power System, when combined with other renewable energy sources, produces a baseload-renewable energy supply that can continuously provide loads.

Features

- Underwater operation and no visible surface features
- Optimized performance and component life with advanced composite materials
- Intended for deployment by locally accessible contractors, equipment and vessels
- Remotely activated buoyancy system with "self-deploying/self-retrieving" towable pontoon support structure
- Low profile as well as advanced design cross-flow turbines
- Encapsulated generators are especially made to last a long time and prevent leaks during underwater operations
- Capable of operating in turbulent conditions with non-linear control system

FIGURE 27. Specifications and key design features of ORPC's RivGen Power System deployed in Igiugig, Alaska. The figure showcases the system's power rating, operating conditions, dimensions, and maintenance requirements, while key features includes advanced composite materials usage, underwater operation, modular deployment, and durability in riverine environments [37].

11) GRID-BASED MES MODELLING

The authors in [144] found three aspects unique to modeling energy grids (level of detail, spatial resolution, temporal resolution) and five general aspects of modeling energy systems (modeling scope, model formulation, spatial coverage, time horizon, data). The general aspects are mostly related to the system boundaries and model scope, whilst the particular features primarily affect the computing effort and the representation of the technical components of the energy system. A number of evaluation criteria, such as economic, energetic, exergetic, and dependability, were established for the modeling findings. The electricity, gas, and district heat networks, as well as energy converters, can be modeled using any of the examined open-source modeling frameworks.

Table 17 summarizes the projects discussed above and lists the key outcomes.

D. GRID INTERCONNECTION AND INTEROPERABILITY WITH IEEE 1547 AND 2030 STANDARD

1) IEEE 1547

The IEEE 1547 standards have significantly influenced utility practices and stakeholder coordination for integrating increasing amounts of distributed energy resources into distribution grids [145]. By offering a framework for incorporating clean, renewable energy technologies along with other distributed generation and energy storage technologies, IEEE 1547 has contributed to the modernization of our electric power systems architecture. In addition to providing flexibility and choices for equipment and operating details that comply with the standard, IEEE 1547 mandates functional technical standards and specifications. Figure 28 shows the IEEE 1547 standards.

2) IEEE 2030

Recently, the IEEE 2030 series of standards has contributed to the increased use of information and communications technologies that offer interoperability solutions for improved DER and load integration with the grid [145]. The 2030 Smart

TABLE 17. Summary of selected marine energy case studies highlighting the application of control, modeling, and simulation techniques, the specific engineering focus of each study, and the resulting system-level performance, efficiency, and integration outcomes.

Projects	Focus Area	Key Outcome
Microgrid Modeling [135]	Community-integrated planning for marine microgrids	Optimized energy mix incorporating community goals
Reactive Blade Tidal Turbine [136]	Blade design to reduce drag and boost output in slow currents	18% peak efficiency at Vtip/U = 0.4
Wave Energy Power Smoothing through Super capacitors [137]	Comparative design of energy storage in wave energy systems	Design 2 more efficient & cost-effective
Mooring Lines [138]	Mechanical modeling of different mooring lines for offshore wind	Validated dynamic models for mooring
FloWatt Pilot Farm [139]	Deployment of 17 MW tidal farm with advanced foundations	Supports 20,000 users; robust grid integration
Carnegie Submerged Wave Energy Devices & Mooring [140]	Subsurface wave devices & adaptive anchoring solutions	Improved deployment flexibility and resilience
HIL Ocean Turbines for Grid Integration [141]	Hardware-in-the-loop testbed for turbine control validation	Effective grid performance under Region 3 operation
PLATform for In-shore energy [142]	Tidal energy converter with trimaran design	Modular and low-resistance design with easy maintenance
RivGen Power System [37]	River current-based power generation integrated with smart grids	Reduces diesel use and connects directly into existing grids using smart grid technology
Attention-ConvNet Network for Ocean-Front Prediction [143]	Hierarchical attention mechanism (HAM), Spatial ConvNet, and hierarchical branching convolutional network (HBCNet)	Provided improved prediction accuracy across the Bohai and Kuroshio ocean-front datasets, according to evaluation studies versus SVR, LSTM, ConvLSTM, GAT, and CFCC-LSTM
Grid-based MES modelling [144]	Specific tools modelling multi-energy systems	Outlined three open-source frameworks for modeling grid-based energy systems, highlighted the main obstacles, and listed the essential factors to take into account when modeling grid-based multi-energy systems

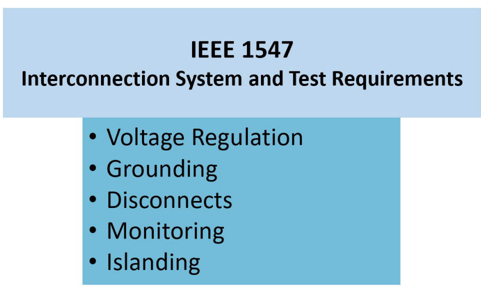


FIGURE 28. Overview of the IEEE 1547 standard outlining key interconnection system and test requirements for integrating distributed energy resources (DERs) with the electric power grid. Voltage regulation, grounding, disconnection, operational monitoring, and islanding requirements to enable safe operation during grid disturbances are the main elements emphasized by the standard shown in the figure [145].

Grid Interoperability Reference Model (SGIRM), which defines integrated architectural perspectives for power systems, communications technology, and information technology; the SGIRM emphasizes functional interfaces, logical connections, and data flows; IEEE Standard 2030 establishes design tables and classification of data flow characteristics, templates for establishing power perspective needs and for identifying and integrating information-communication technology protocols, standards, etc., addressing reliability, security, cyber, quality of service, and communication mediums.

Since MHK technologies and offshore wind, particularly floating platforms, both depend on power-electronic interfaces for grid connection, compliance with IEEE 1547 and 2030 is essential for system design and implementation.

VII. CONCLUSION AND DIRECTION FOR FUTURE RESEARCH

It is challenging to develop new electricity-producing technology, particularly for marine energy. Any design requires several iterations to completely develop, test, and optimize; a single design cycle can take years when working in the water with massive equipment and dealing with several non-technical issues. This paper evaluated the current resource capacity, global deployment status of Marine Hydrokinetic and Offshore Wind technologies across North America, South America, Europe, Asia, and Australia, and listed ongoing global projects in order to fill the gap in a direct comparative review of these technologies. Furthermore, focusing on the progress in integration techniques and hybrid system development, a rigorous analysis of existing pilot projects and demonstrations has been conducted. These practical applications highlight the current level of technical maturity as well as the persistent challenges that must be resolved before widespread adoption is feasible. In addition to providing a basis for identifying important gaps, benchmarking advancements, and directing future research and deployment plans in this field, these findings will aid researchers in assessing the readiness levels of both MHK and OSW technologies.

A. IDENTIFIED GAPS

A few identified gaps that are hindering the integration of marine hydrokinetic energy and offshore wind technology are discussed below:

- **Lack of a standard framework:** The absence of a standardized framework is the most critical technological gap that hinders fair, side-by-side comparisons of device types and geographical regions, which makes it more difficult for investors to assess feasibility, researchers to measure progress, and set obvious deployment targets.
- **Limitation in resource characterization:** Long-term performance prediction accuracy is decreased by the current models' frequent inability to capture

site-specific variability in offshore wind, currents, and waves.

- **Inconsistency in technological maturity:** MHK technologies are still mostly at the demonstration or planning stage; however, OSW is moving closer to commercial application.
- **Challenges in grid integration:** When both technologies are integrated, the grid faces difficulties such as unstable power, inadequate reactive power, poor power quality, and reduced grid resilience.
- **Issues in operation and maintenance:** The location of turbines being far from the shoreline creates challenges in operation and maintenance.

B. FUTURE RESEARCH DIRECTION

Despite numerous challenges, significant advancements have already been achieved in combining marine hydrokinetic energy and offshore wind energy research and development. Within the next decade, there is a strong chance for installing and commercially operating full offshore wind-wave farms and to direct future research in this area, an analytical framework centered on taxonomy, comparison matrix, cost, benefit meta-analysis, or standardized performance metrics must be developed. Based on the gaps and limitations identified in the existing literature, the authors propose the following future research directions to further develop and integrate MHK and OSW technologies:

- Establishing a uniform, globally acknowledged set of analytical, technical, and conceptual frameworks for MHK and OSW systems to allow for proper cross-comparison of deployment regions and technologies, which will promote regular reporting of efficiency and capacity factors.
- Incorporating a comparative evaluation matrix or framework based on resource characteristics, structural configurations, TRLs, deployment depth, cost composition, economic viability, technology maturity, Capex/Opex, environmental effects, O&M requirements, and grid-integration difficulty is highly needed.
- Further investigation is needed into the co-location of hybrid OSW–MHK farms, including offshore substations, subsea cabling, and shared mooring.
- Future studies should focus on how wind and wave resources might be combined to smooth power output and lessen intermittency.
- More focus should be given to developing hard-in-the-loop and power hardware-in-the-loop models in order to validate the real-time performance of the developing devices under realistic ocean conditions.
- In order to determine the effects of large-scale OSW and MHK penetration on island and coastal grids, more thorough studies are required. Advanced control techniques for frequency stability, reactive power support, and microgrid operation should be given priority in future research.
- Extensive studies on offshore hydrogen integration are necessary to completely utilize the electricity produced by offshore wind farms for hydrogen production [146].
- More emphasis should be placed on digital twin modeling for wind turbine applications to follow the farms throughout their life cycles, evaluate component states, direct predictive maintenance, and develop full-scale prototypes [147].
- More research is required to determine how marine energy resources can provide unique and significant advantages to various grid designs, such as the bulk system, isolated distribution systems, remote villages, islands, and microgrids, as marine energy resources can be useful for enhancing a generation portfolio's technological diversity, promoting local resilience, and both complementing and being complemented by other resources [148].
- To increase forecasting accuracy and characterize resources (waves, tides, currents, and wind profiles), more attention should be given to utilizing artificial intelligence and machine learning, including Bayesian optimization, systematic optimization of learning rate, dropout rate, batch size, and optimizer settings.
- Extensive reserach on biofouling mitigation techniques for MHK devices as well as ethical discussion addressing potential biases in regional water data is needed.
- Further research is needed to assess the economic viability of co-located offshore wind and marine hydrokinetic systems.

In conclusion, this review emphasizes the fact that the successful large-scale deployment of offshore wind and marine hydrokinetic systems depends on addressing the lack of a standardized framework, a unified comparison matrix, resource characterization accuracy, and grid-integration strategies, thus creating a focused future research direction in hybrid system design, advanced control, implementation of artificial intelligence, and data-driven forecasting.

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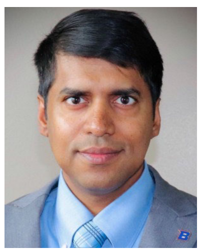

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