

Review

Hybrid Offshore Wind and Wave Energy Systems: A Review

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Abstract

Against the backdrop of the global energy transition, the efficient exploitation of marine renewable energy has become a key pathway toward achieving carbon neutrality. Wind–wave hybrid systems (WWHSs) have attracted growing attention due to their resource complementarity, efficient spatial utilization, and shared infrastructure. However, most existing studies focus on single components or local optimization, while systematic integration of the full technology chain remains limited. This gap hinders the transition from demonstration projects to commercial deployment. This review provides a comprehensive overview of the technological evolution and key characteristics of offshore wind turbine (OWT) foundations and wave energy converters (WECs). Fixed-bottom foundations remain the mainstream solution for near-shore development. Floating offshore wind turbines (FOWTs) represent the core direction for deep-sea deployment. Among WEC technologies, oscillating buoy (OB) WECs are the dominant research pathway. Yet high costs and poor performance under extreme sea states remain major barriers to commercialization. On this basis, the paper summarizes three major integration modes of WWHSs. Among them, hybrid configurations have become the research focus due to their structural sharing, hydrodynamic coupling, and significant cost and energy synergies. Furthermore, the review synthesizes optimization strategies for both technology design and spatial layout, aiming to enhance energy capture, structural stability, and overall economic performance. Finally, the paper critically identifies the main research gaps and technical bottlenecks and outlines key development pathways required to achieve future commercial viability. These include the development of high-performance adaptive power take-off (PTO) systems, deeper understanding of multi-physics coupling mechanisms, intelligent operation and maintenance enabled by digital twins, and comprehensive life-cycle techno-economic and environmental assessments. Through this integrated perspective, the review seeks to provide a systematic reference for the development of multi-energy offshore systems and to support future progress in integrated energy utilization in deep-sea environments.

Keywords: offshore wind energy; wave energy; wind–wave hybrid systems; layout optimization; hydrodynamic coupling; multi-energy complementarity



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1. Introduction

Over the past several decades, the rapid expansion of global industrial sectors, coupled with delayed environmental protection measures, has led to a significant deterioration of the human living environment [1,2]. Since 1950, global energy consumption has increased by a factor of 5.8, and it is expected to rise to 11.6 times by 2050 [3]. Meanwhile, atmospheric CO₂ concentration has surged from 310 ppm in 1950 [4] to 425 ppm in 2025 [5], reflecting a severe trend in greenhouse gas emissions. Excessive use of fossil fuels, as a key driver,

has intensified air and water pollution, soil degradation, and the release of large quantities of harmful substances into the environment [6]. Against this backdrop, the development of low-cost and environmentally friendly renewable energy alternatives has become an urgent requirement to ease pollution pressures [7,8]. In response to this global challenge, the United Nations Sustainable Development Goals (UN-SDGs) and the Paris Agreement have set constraints and guidance to encourage countries to expand renewable energy deployment to mitigate climate and environmental risks [9,10]. The European Union has also established phased targets: renewable energy should account for 20% of electricity generation by 2020 (with at least 10% for each member state), and 32% by 2030 as a mid-term objective [11], thereby institutionalizing the energy transition. With global energy demand continuing to rise and climate pressures intensifying, the integration of renewable energy into power systems is expanding rapidly [12], and it is recognized as an essential pathway to achieving the emission-reduction goals of the Paris Agreement; it is estimated that at least 63% of global electricity must be generated from renewable sources to meet these goals [13]. Renewable energy development covers both onshore and offshore domains, with offshore resources receiving increasing attention due to their abundance and long-term potential. However, offshore systems face engineering challenges such as limited space, heavy equipment, and high installation costs [14]. Despite these challenges, offshore energy hubs are playing an increasingly important role in decarbonizing marine transportation, offshore oil and gas operations, and mariculture, with their energy supply gradually shifting from traditional diesel and fossil fuels [15] toward renewable sources. As the share of renewable energy continues to grow, the cost of offshore power generation is expected to decline further [16].

Among various forms of offshore renewable energy, wind and wave energy have become the most representative resources due to their abundance, high availability, and ongoing technological advancement. However, single-source offshore wind power cannot satisfy the demand for efficient and stable energy supply, whereas wave energy, with its high energy density and wide spatial distribution, is considered one of the most promising marine renewable resources [17]. At the same time, wave energy development faces non-negligible economic constraints. Its levelized cost of electricity has remained relatively high, which to some extent limits large-scale commercial deployment [18]. It is noteworthy that wind and wave energy exhibit strong spatial and physical correlations. Regions with abundant wind resources often coincide with rich wave energy, and the two also demonstrate significant temporal and spatial complementarity [19], creating a natural synergy that provides a robust foundation for their joint development [20]. In contrast, single-energy systems commonly suffer from strong power fluctuations, low device utilization, and high levelized cost of energy, which severely constrain their economic viability and supply stability. Therefore, “wind–wave” hybrid systems (WWHSs) offer a new technological pathway to overcome these limitations. Such hybrid systems integrate wind turbine foundations with wave energy converters (WECs), which can significantly improve offshore space utilization [21,22]. They also reduce construction and operational costs through shared platforms, mooring systems, and power transmission infrastructure [23,24], while minimizing disturbance to the marine environment [22]. As a result, they enhance both economic performance and supply stability. In terms of power output, the high predictability and stability of wave energy can compensate for the intermittency and uncertainty of wind power, thereby improving overall energy capture efficiency and output continuity [25,26]. In terms of structural safety, wave energy devices can partially absorb wave loads, reducing wave impacts and run-up on marine structures, and lowering the loads on the foundation [27], which enhances system safety and durability. Given these technological and economic advantages, the coordinated development of wind and wave energy is considered a key

pathway toward the commercial application of wave energy [28], and it establishes an essential technical foundation for multi-energy offshore renewable systems.

Although WWHs have emerged as an important direction in marine renewable energy due to their resource complementarity, improved spatial efficiency, and potential cost synergies, the volume of related research has continued to grow in recent years. Existing review studies have summarized this field from multiple perspectives, including power coordination mechanisms, electrical system integration, floating platform demonstrations, and joint site planning [29–32]. These efforts have laid a solid foundation for understanding the technical feasibility and engineering potential of WWHs. However, from a broader perspective, the current literature remains fragmented in terms of system classification, technology comparison, and synthesis of development trends. In particular, a systematic and comprehensive assessment is still lacking for hybrid systems combining fixed and floating foundations, especially with regard to integration mechanisms, enabling technologies, and layout optimization strategies. Against this background and in view of recent technological advances, this paper organizes the research progress of WWHs, referred to as WWHs, along a clear line of inquiry that moves from technological evolution to system integration, then to performance optimization and finally to engineering prospects. Unlike existing reviews that often focus on a single device or a specific aspect, this work emphasizes the construction of a unified analytical framework that spans foundation types, WEC configurations, coupling modes, and system level performance optimization. The aim is to reveal the intrinsic connections and development patterns among different technical routes, while offering several original contributions. By linking technological optimization with layout optimization, this study develops a system level perspective of coordinated analysis that provides theoretical support for overall system design, array planning, and multi energy coupling strategies in WWHs. It further proposes a coherent framework centered on technological evolution, system integration, and performance optimization, within which fixed, floating, and hybrid systems are examined in a unified comparative context. Based on this framework, the paper systematically reviews the technological development pathways of WWHs and identifies key research gaps through integrated analysis, including cross system coupling, multi objective optimization, adaptability to extreme sea states, and ecological impacts. These insights are intended to offer clear guidance for future research in this rapidly evolving field.

In terms of research methodology, this paper combines a systematic literature review with comparative analysis to synthesize and integrate existing studies. The literature was mainly retrieved from major databases such as Web of Science, Scopus, and ScienceDirect, with particular emphasis on high-quality publications from the past five years (2020–2025) to ensure both the timeliness and representativeness of the review. On this basis, the discussion focuses on four key aspects: (1) the technical characteristics of different offshore wind turbine (OWT) foundations and WECs, as well as their applicable scenarios; (2) the dominant coupling forms and structural integration mechanisms in WWHs; (3) optimization strategies related to energy capture, hydrodynamic response, and array layout, together with their engineering implications; and (4) the critical scientific and engineering challenges that remain to be addressed in current research.

The structure of this paper is organized as follows. Section 2 reviews the development of offshore wind foundations and wave energy devices, establishing the technical background for studies on hybrid systems. Section 3 systematically summarizes the coupling modes of different types of WWHs and, through comparative analysis, highlights the differences in their structural and hydrodynamic characteristics. Section 4 further synthesizes performance optimization approaches from both technological and layout perspectives, identifying key common issues in current research. Finally, Section 5 presents the over-

all conclusions and outlines future research directions based on the integrated analysis. Through this organization, the paper aims to reflect the essential qualities of a high-quality review, including systematic coverage, comparative insight, and a forward-looking perspective, thereby providing valuable references for future research and engineering applications of WWHs.

2. Research Progress on OWT Foundations and Wave Energy Devices

The performance of WWHs depends strongly on the technological maturity of OWT foundations and WECs. Their compatibility directly determines the coupling efficiency and engineering feasibility of hybrid systems. This section therefore reviews the technological pathways, application scenarios, and development trends of OWT foundations and WECs, providing a solid technical basis for the subsequent analysis of integration modes in WWHs.

2.1. Research Progress on OWT Foundations

In recent years, with the continued implementation of China's clean energy strategy, offshore wind power has become an integral part of the renewable energy system [33]. However, the development of offshore wind energy relies not only on domestic policies but also benefits from advancements in offshore wind technology worldwide [34]. Compared with onshore wind resources, offshore wind fields offer more stable wind conditions, higher energy utilization efficiency, and greater power density, while the choice of foundation type directly affects engineering feasibility, structural safety, and overall economic performance. Significant regional differences in seabed geology, water depth, wave–current conditions, and construction capabilities have also driven the evolution of OWT foundations and the development of multiple technological pathways.

At present, OWT foundations worldwide can be broadly classified into two categories: fixed foundations and floating foundations (FOWTs) [35] (Figure 1), corresponding to applications from shallow to deep waters. Fixed foundations are mainly used in shallow and intermediate water depths and represent the most mature and widely deployed technologies. Typical structures include monopile foundations [36], jacket foundations [37,38], gravity-based foundations [39], and the rapidly developing composite bucket foundations (CBFs) [40,41]. Monopiles are widely used in shallow waters, such as China's eastern coast and the North Sea, due to their simple construction and relatively low cost. Jacket foundations perform well in intermediate depths and complex geological conditions and are suited for larger loads or sites with higher geotechnical demands. Gravity-based and composite bucket foundations rely on large structural dimensions for stability [42], making them suitable for areas with favorable geology or where construction disturbance must be minimized. With continuous progress in construction equipment, materials, and installation technologies, fixed foundations are expanding in both economic viability and applicable water depths.

In contrast, floating foundations are designed to overcome water-depth limitations in deep-sea wind power development and represent a major future direction for the offshore wind industry [30]. The main floating foundation types include semi-submersible platforms [43], tension-leg platforms (TLPs) [44], and spar-type platforms [45]. Semi-submersible platforms are currently the most widely adopted structures in deep-sea research and demonstration projects due to their low center of gravity, good stability, flexible layout, and broad water-depth applicability. TLPs offer excellent vertical stability but depend heavily on mooring systems and remain costly. Spar platforms rely on deep-draft ballast to provide restoring moments and have simple structures and small wave-induced motions, but they face challenges such as high tower-fatigue loads and stringent deep-

water installation requirements. Although floating foundation technology has already been demonstrated in Europe and the United States, it remains in the engineering validation and optimization stage and has not yet achieved large-scale commercial deployment [46]. Representative examples include the Hywind Spar deployed by Equinor in 2009 with a 2.3-MW turbine [47] and the WindFloat semi-submersible platform installed off the Portuguese coast in 2011 [48]. In recent years, China has also deployed several floating wind power demonstrators, including the “Three Gorges Leading” semi-submersible platform in 2021, “Fuyao” in 2022, and “CNOOC Guanlan” in 2023, gradually accumulating technological and engineering experience. Reference [46] provides a systematic review of floating foundation designs.

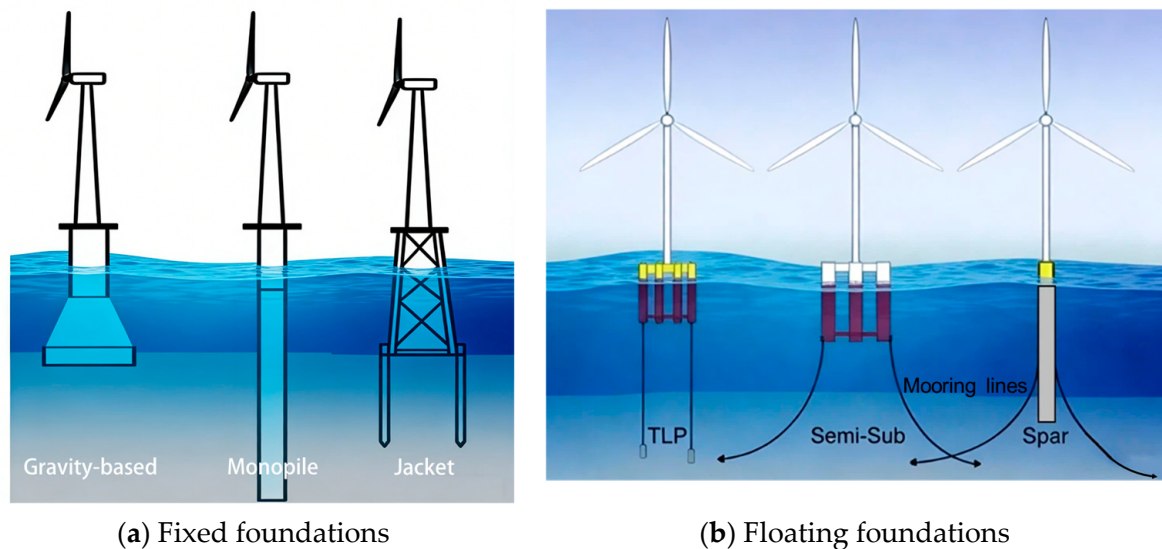


Figure 1. Types of OWT.

Overall, OWT foundation technologies are evolving along two parallel paths: fixed foundations dominate near-shore regions, while floating foundations enable breakthroughs in deep-sea development. Fixed foundations will continue to dominate near-shore applications due to their maturity, controllable cost, and extensive installation experience, with research focusing on lightweight structures, improved adaptability to complex seabed conditions, and enhanced construction efficiency. Floating foundations are considered the key technological route for deep-sea wind power and continue to attract global attention, with research concentrated on mooring-system optimization, motion-response control, durability enhancement, cost reduction, and large-scale deployment [25]. The parallel development of these two foundation types supports the large-scale growth of offshore wind power and lays the technical foundation for future expansion into deeper waters, harsher sea states, and larger turbine capacities.

2.2. Research Progress on WECs

Wave energy, as a major category of marine renewable resources with vast reserves, wide distribution, and high energy density, has long attracted significant attention from both academia and industry. Wind turbines have already been demonstrated through many commercial projects, whereas wave energy remains far from commercial deployment because of its high cost [49]. At the global level, wave energy is mainly harvested for power generation, and WECs exhibit diverse structural forms. Their performance directly determines energy capture efficiency, environmental adaptability, and engineering potential. Based on structural characteristics and energy extraction mechanisms, existing wave

energy devices mainly include oscillating body types [50,51] (Figure 2a), oscillating water column (OWC) devices [52–54] (Figure 2b), and overtopping devices [55–57] (Figure 2c), as summarized in Table 1. Each type exhibits distinct differences in suitable sea states, structural features, conversion efficiency, and engineering complexity.

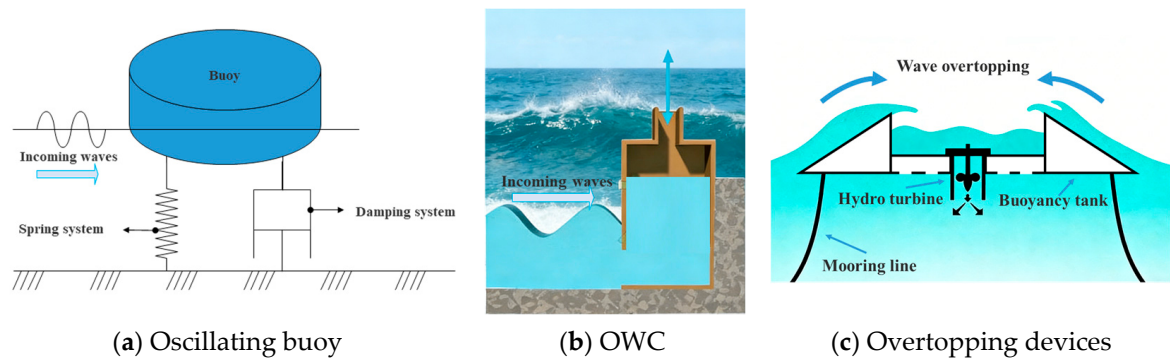


Figure 2. Types of WEC.

Table 1. Classification of WECs.

WECs	Oscillating Bodies	Oscillating Water Column	Overtopping
Working principle	Utilizing reciprocating body motion of waves	Air turbine driven by air compressed by wave energy	Hydro, air, or hydraulic type turbine driven by wave energy

Oscillating body WECs can be further divided into three core configurations: (1) point absorbers that capture energy through heave motion; (2) terminators that extract energy from surge motion; and (3) attenuators that utilize pitch motion to absorb wave energy [58]. Among developed oscillating body WECs, point absorbers account for 53%, terminators for 33%, and attenuators for the remaining 14% [59]. Point absorber WECs have become the mainstream development pathway because of their compact structure, broad adaptability, simple design, high conversion efficiency, and stable power output [60]. The oscillating buoy (OB) WEC, as a key technical branch of point absorbers, further strengthens this pathway due to its simple configuration, small size, ease of fabrication, and convenient offshore installation. It has become one of the most active research directions. However, extreme marine conditions—such as typhoons, high waves, and sea ice—pose severe challenges to the floating structure and mooring system. Strong wave loads may cause fatigue failure or mooring line breakage. Seawater corrosion and marine biofouling (e.g., mussels and algae) increase drag, reduce response sensitivity, shorten maintenance cycles, and raise costs. Therefore, improving environmental robustness is a key requirement for engineering applications of these devices. The operating principle of this type of device is to exploit the resonance between the floating body and incident waves, thereby efficiently transferring wave energy to the power take-off (PTO) system [61]. However, its practical engineering application faces serious challenges. Extreme marine conditions, such as typhoons and severe waves, can easily induce structural fatigue and mooring failure. At the same time, seawater corrosion and biofouling increase hydrodynamic resistance, reduce system sensitivity, and raise maintenance costs. Enhancing environmental robustness is therefore a critical requirement. Against this background, control strategies for PTO systems have become central to improving both energy capture efficiency and operational stability. Early studies mainly focused on passive damping control by optimizing the damping level to match the resonance frequency. In recent years, active and intelligent control strategies have developed rapidly. Representative approaches include model predictive control based

on wave forecasting to optimize energy capture trajectories [62], maximum power point tracking to maximize real-time power output [63], and machine-learning-based adaptive control strategies [64]. Together, these methods have significantly improved conversion efficiency and overall system robustness under wave excitation. Structurally, single-body point absorbers include two major categories: the floating-type, exemplified by the Sea-based device [65], and the fully submerged type, represented by the CETO device [66]. Such single-body systems typically include a heaving float that moves relative to a fixed reference, such as the seabed. Several representative devices have been developed, including the OPT PowerBuoy [67], Wavebob [68], Inter Project Service devices [69,70], the Uppsala University WEC [71], Oyster [72], FO3, IPS devices, and the Lysekil system [73,74]. Owing to their compact configuration, strong environmental adaptability, and good scalability, oscillating-buoy devices show great potential for application in nearshore and intermediate-depth waters. In addition, to enhance overall energy capture, recent research has shifted from evaluating individual device performance to exploring array effects, focusing on optimizing layouts of multiple point absorbers. These developments provide an important foundation for large-scale deployment and commercialization of oscillating body WECs [75–77].

OWC device [78–80] is another relatively mature form of wave energy utilization. Its core working principle is based on a closed or semi-closed air chamber fixed to the shoreline or nearshore seabed. Incoming waves drive the water column inside the chamber to oscillate vertically. The air above the water column is then periodically compressed and expanded, producing a bidirectional airflow that rotates an air turbine installed at the chamber top, thereby converting wave energy into electrical power with good reliability and durability. Structurally, OWC devices are generally large. The air chamber and associated components require significant seabed bearing capacity, making site selection highly dependent on robust nearshore terrain. As a result, deployment in offshore deep-water environments remains challenging, and these systems are commonly used in shoreline or nearshore settings. With advances in chamber optimization, turbine efficiency, and integrated design, OWC technology has been demonstrated in several countries.

Overtopping wave energy conversion [55–57] technology uses the overtopping phenomenon as its core energy capture mechanism. The key design requirement is that the reservoir must maintain a water level higher than the surrounding sea surface. The operation process is as follows: incident waves run up along the sloping front structure and overtop into the reservoir, generating a stable potential head difference; the stored water is then released through a designed channel to drive low-head axial-flow turbines, realizing efficient conversion from wave energy to electricity. Compared with other types of WECs, overtopping devices have several advantages. First, they convert highly fluctuating and random wave energy into more stable potential energy, enabling effective smoothing of power output and improving supply reliability and operational flexibility. Second, low-head hydraulic turbine technology is mature in hydropower engineering, and the associated design, manufacturing, and maintenance experience can be directly transferred, reducing technology development barriers and engineering validation costs. However, this technology still faces significant challenges. In terms of sea-state adaptability, its performance is highly sensitive to wave parameters such as height, period, and incident angle. Under small or irregular waves, insufficient overtopping may occur, causing a marked decline in conversion efficiency. From an engineering perspective, the system requires large integrated structures such as slopes and reservoirs, resulting in substantial size and weight. This increases transport and installation complexity and imposes higher demands on mooring capacity and stability. Furthermore, its applicability is strongly constrained by local bathymetry and seabed conditions. Energy dissipation due to wave breaking in shallow waters, and mooring complexity in deep waters, may limit overall performance.

Nearshore deployment also requires balancing coastal ecological protection and visual impact considerations, making large-scale standardization difficult.

From the overall development perspective, current research in academia and industry focuses on several directions:

- (1) Optimization and expansion of device structural forms, including floater geometry [81–83], device scale, and array layout, to improve energy capture efficiency and operational stability;
- (2) Enhancing the performance of power take-off (PTO) systems [84–87] and innovating control strategies are central to improving overall power generation efficiency. Beyond conventional damping control, recent research has expanded toward advanced approaches such as model predictive control [62], optimal control [63], and machine-learning-based adaptive control [64]. These strategies aim to achieve efficient broadband energy capture while ensuring stable system operation. In particular, they show strong potential for coping with complex and highly variable sea states.
- (3) The application of multi-degree-of-freedom energy absorption mechanisms [83] is also increasing. By jointly harvesting wave energy from multiple directions [78–80] and optimizing motion trajectories through coordinated control strategies, these systems significantly enhance energy conversion performance under broad-spectrum wave conditions.
- (4) At the system level, development is shifting from single devices toward array-based and integrated configurations. This trend is especially evident in WWHSSs, where coupling with offshore wind farms introduces new interaction effects among devices that influence both energy capture and platform stability. As a result, array-level coordinated control and energy dispatch have emerged as key research topics in recent years.

Overall, WECs have achieved significant progress in structural forms, energy conversion mechanisms, control strategies, and engineering applications. However, challenges remain in cost, reliability, maintenance convenience, and adaptation to complex sea conditions. With advances in materials, intelligent control, and multi-energy coupling platforms, future wave energy devices are expected to achieve more efficient, economical, and widely adaptable applications.

3. Research Progress of WWHSSs

Building on the systematic review in Section 2 of the technological evolution of OWT foundations and WECs, this section further focuses on the system-level integration modes and coupling mechanisms between wind and wave energy. Compared with single-energy devices, the core scientific and engineering challenges of WWHSSs have shifted from improving the performance of individual units to understanding multi-device coupling mechanisms, system-level synergy, and comprehensive performance optimization. It is therefore necessary to conduct a systematic review and comparative analysis of existing studies from the perspectives of physical coupling intensity, structural sharing modes, and the level of functional integration.

Based on the available literature, WWHSSs can generally be classified into three categories: co-located systems, island systems, and hybrid systems [88], as illustrated in Figure 3. This classification not only reflects differences in engineering complexity and technological maturity, but also corresponds to an evolutionary pathway from weak coupling toward strong coupling. The following sections discuss these three system types in detail, with a focus on comparing their technical characteristics, research priorities, advantages, and limitations. On this basis, current research trends and key knowledge gaps are further identified.

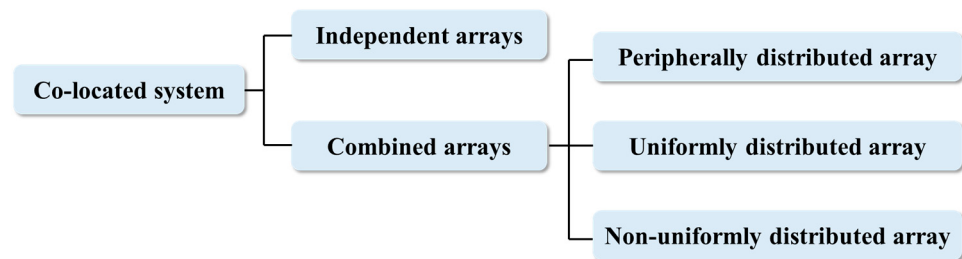


Figure 3. Classification of co-located systems.

3.1. Co-Located Systems

Co-located systems represent the most technically mature and least complex option for engineering implementation in wind–wave joint development. Their defining feature is that wind turbines and WECs are deployed in the same sea area, while remaining structurally and dynamically independent. Each system has its own foundation, mooring arrangement, and power conversion unit [89]. This mode is usually built around existing or planned offshore wind farms, with WEC arrays arranged inside or around the wind farm. A certain degree of synergy is achieved through the shared use of sea space, grid connection facilities, operation and maintenance resources, and port infrastructure [90].

From the perspective of system layout, co-located systems can be further divided into two main types, namely independent arrays, as shown in Figure 4, and combined arrays. According to the spatial distribution of WECs within the wind farm, combined arrays can be classified into peripheral distributed arrays (PDA), uniform distributed arrays (UDA), and non-uniform distributed arrays (NDA) [91]. In PDA, WECs are typically deployed along the wave-ward boundary of the wind farm. By absorbing and scattering incoming waves, they create a wave sheltering zone inside the array, which can reduce the wave loads acting on wind turbine foundations to some extent, as illustrated in Figure 5a. UDA embed WECs evenly among wind turbines. This configuration emphasizes efficient use of sea space and maximization of total system energy output, as shown in Figure 5b. NDA further accounts for multi-body hydrodynamic interactions. Through non-uniform placement, they aim to achieve localized performance optimization, as depicted in Figure 5c.

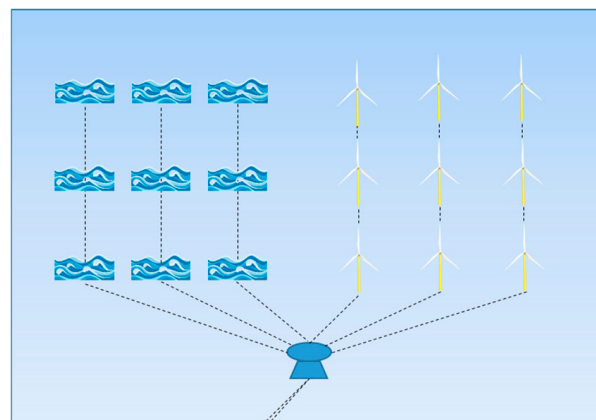


Figure 4. Independent array.

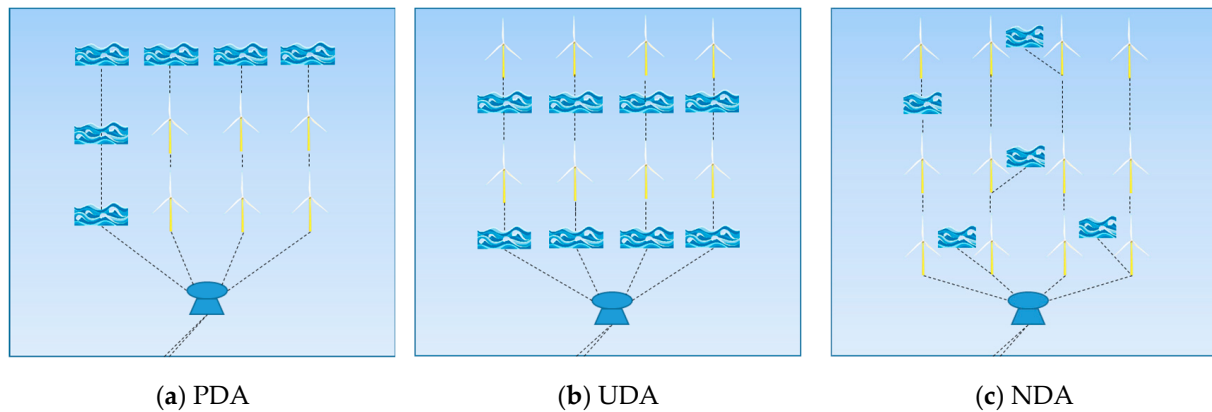


Figure 5. Combination array.

Overall, the main advantages of co-located systems lie in their design flexibility, low technical risk, and suitability for phased deployment. They are particularly well suited to nearshore waters and pilot-scale projects. However, because deep integration at the structural and dynamic levels is lacking, the synergistic benefits are mainly limited to operation, maintenance, and grid connection. As a result, the complementary potential of wind and wave resources cannot be fully exploited. Improvements in output stability, energy density per unit sea area, and long-term economic performance remain relatively constrained. Co-located systems are therefore better regarded as a transitional solution or an early-stage validation pathway for wind–wave joint development, while their long-term competitiveness in deep-water and high-energy-density regions is still limited.

3.2. Island Systems

Island systems represent a highly integrated and multifunctional approach to wind–wave joint development. Their central concept is to consolidate wind energy, wave energy, and potentially energy storage, hydrogen production, and offshore operational capabilities within a single energy hub using large artificial or floating platforms. Depending on the type of foundation, island systems are generally classified into artificial energy islands and floating energy islands [91], as illustrated in Figure 6.

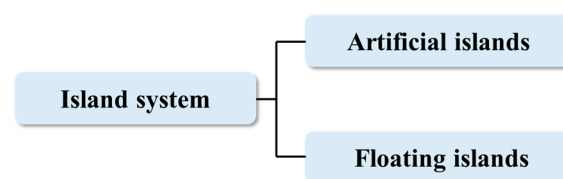


Figure 6. Island system classification.

Artificial energy islands are typically built on large dikes, artificial reefs, or reclaimed bases. They offer high load-bearing capacity and stable foundations, serving as platforms for large-scale energy integration, storage, and other marine activities. The Kema Energy Island concept proposed by Dutch consultancy DNV KEMA is a typical example. This project aims to integrate wind, wave, and large-scale energy storage for multi-energy coordinated development [92]. Artificial islands are suitable for shallow and medium-depth waters, can accommodate complex energy facilities, reduce interference among devices, and improve power output stability. However, they involve high construction costs, long installation periods, and are constrained by seabed conditions and environmental factors.

Floating energy islands are large multi-purpose floating platforms. They are smaller than artificial islands but still much larger than conventional vessels, allowing integration

of multiple marine energy sources. Floating islands offer flexibility and suitability for deep-water deployment, making them ideal for offshore wind–wave development [93]. For example, the 50 MW floating energy island project proposed by Energy Island Ltd. in the UK integrates wind turbines and WECs on a floating platform for efficient energy capture and multi-functional use [94]. Floating islands provide mobility and deep-water adaptability but require careful design of buoyancy, stability, mooring systems, and coordinated power control. Island systems enable highly integrated use of marine space and have the potential to become key platforms for offshore multi-energy development. With the advancement of energy storage and smart grid technologies, island systems are expected to serve as important carriers for offshore energy integration and dispatch, providing sustainable, stable, and efficient solutions for hybrid wind–wave power generation.

Overall, island systems offer significant advantages in terms of energy integration and efficient spatial utilization. However, their engineering complexity and high investment requirements make them more suitable as a medium- to long-term development pathway, and large-scale commercial deployment remains challenging at the current stage.

3.3. Hybrid Systems

WWHSs are currently the most studied and technically diverse offshore energy utilization mode in academia and industry. Their core feature lies in the structural coupling or sharing among different energy conversion devices. By arranging devices jointly, these systems enhance energy capture, reduce structural loads, and lower costs. Compared with co-located systems, hybrid systems are not only spatially interdependent but also achieve multi-level coupling in structure, dynamics, and power output. This makes them a key development direction for future offshore multi-energy platforms. Hybrid systems can be classified by foundation type into (1) bottom-fixed hybrid systems and (2) floating hybrid systems, as shown in Figure 7.

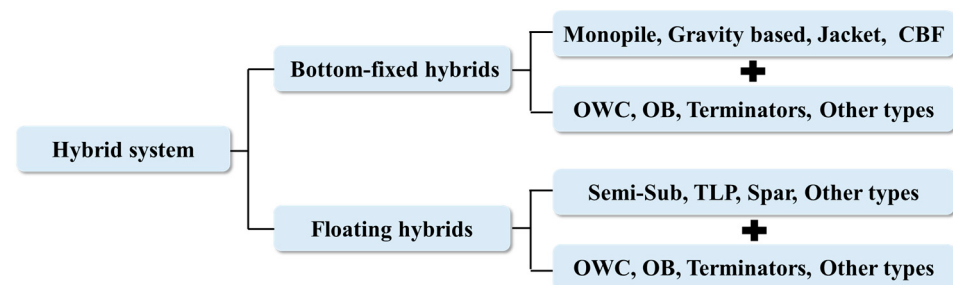


Figure 7. Hybrid system classification.

3.3.1. Bottom-Fixed Hybrid Systems

Bottom-fixed hybrid systems represent one of the mainstream technological pathways for nearshore wind–wave joint development, primarily targeting coastal and shallow-water areas. The core concept involves integrating wave energy converters with well-established fixed offshore wind turbine support structures, such as gravity-based foundations, monopiles, and jacket foundations. These systems offer clear advantages in terms of construction procedures, structural stiffness, and operational accessibility, making them one of the most mature technological approaches in current hybrid system research.

Among various integration schemes, combining OWC devices with fixed foundations is a major research direction. Integration with monopiles mainly appears in two forms: one involves cutting openings in the monopile to use its internal cavity as the OWC chamber [95]; the other installs an independent “hooded” structure around the monopile to form the chamber [96–99]. Compared to monopiles, jacket foundations provide more flexible integration space for OWC devices. For example, Perez-Collazo et al. proposed

placing the OWC device at the central region of the jacket structure to form a compact wind-wave hybrid unit [100].

Beyond OWC-based systems, OB WECs exhibit diverse technologies and offer rich integration concepts with wind turbine foundations. Oscillating and pitching buoys derived from mature WEC devices such as WaveBob and WaveStar are the primary forms integrated with wind turbines.

For monopile-supported hybrid systems, a wide range of design concepts exists. OBs are often hollow ring structures placed around the monopile and guided to oscillate vertically (Figure 8a), with SEACAP [101] and MWWC [102] as typical examples. Pitching buoys are connected at one end to the monopile via a hinged arm and at the other end to the top of the buoy. These buoys vary in shape, including spherical [103], hemispherical [104], and semi-ring [105,106], with usually more than two units. Innovative concepts continue to emerge. For instance, Li et al. [107] proposed splitting a ring buoy into three identical buoys arranged around a monopile turbine, studying hydrodynamic interactions and coupling under different PTO damping (Figure 8b). Subsequent studies analyzed wave load characteristics of a 15 MW monopile-ring buoy hybrid system [27] (Figure 8a). Multiple studies indicate that arranging several OB WECs around or below a monopile significantly improves power capture [105], with WEC quantity, radial distance, and PTO damping as key design parameters [104]. Integration concepts extend to other foundation types. Pitching buoys can be combined with jacket wind turbines [108]; OBs can be integrated with CBFs (Figure 8c) [109]; multiple OBs can also be installed on gravity foundations [110]. These examples demonstrate the technical diversity and adaptability of bottom-fixed hybrid systems. However, significant differences exist among studies in terms of wave conditions, device scale, and evaluation metrics, which limits the comparability of their results.

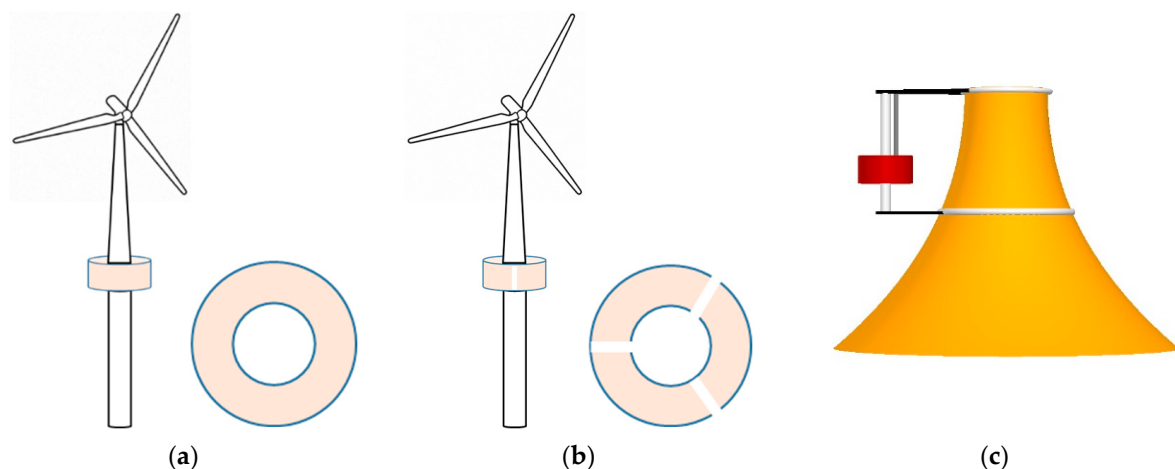


Figure 8. Integrated schematic diagram of fixed foundation and OB. (a) Hollow annular buoy integrated with monopile, adapted from [27]; (b) Monopile integrated with segmented buoy, adapted from [107]; (c) CBF integrated with cylindrical buoy, adapted from [109].

Overall, bottom-fixed hybrid systems have gradually transitioned from early conceptual designs to performance assessment stages. Nonetheless, their engineering applicability remains highly dependent on specific sea conditions and wind turbine scales, and a unified set of design guidelines and evaluation criteria has yet to be established.

3.3.2. Floating Hybrid Systems

Floating hybrid systems are primarily designed for intermediate to deep and deep-water sites, with research focusing on the multi-body dynamic coupling between WECs and floating wind platforms. Compared with bottom-fixed systems, floating systems exhibit

greater diversity in their configurations, but they also pose higher challenges in terms of motion control and structural safety. In these cases, wind turbines are usually single units, while OWC devices are typically two or more, such as three [111] or four [112] OWCs evenly distributed around a monopile, a TLP combined with three OWCs [113], four OWCs installed at the corners of a square barge platform [114,115], and semi-submersible platforms combined with two or three [116–118] OWCs.

Although most operational offshore wind farms currently use fixed turbines, floating foundation integration with wave energy devices exhibits more diverse forms than fixed systems. Spar floating wind turbine foundations resemble fixed monopiles in shape. Therefore, the integration of OBs with wind turbines in hybrid units is also similar. Examples include STC [23] and HWNC [119], which consist of ring-type OBs with Spar, and concepts combining conical cylindrical [120] or spherical [103] pitching buoys with Spar turbines. TLP wind turbines combined with OB WECs are less common. Based on buoy quantity, these hybrid units can be divided into single-buoy [121,122] and multi-buoy configurations [123,124]. Compared to Spar floating wind turbines and TLPs, semi-submersible platforms offer a wider range of water depths and lower mooring installation costs [125], making them the most common foundation type for wind-wave hybrid units. OB WECs integrated with semi-submersible turbines are also classified as oscillating [126,127] or pitching [28,125,128–130]. Main semi-submersible platforms used for integration include DeepCwind [129,131], WindFloat [126,127], and braceless [125,130], with novel forms such as hexagonal designs [128]. Tian et al. [132], Zhou et al. [133], and Homayoun et al. [134] systematically studied the coupling between semi-submersible platforms and various OB types. They analyzed the relationships among platform motion, PTO damping, and power generation. Results show that buoy quantity, geometry, and damping configuration can optimize system power output and motion response by altering added mass and multi-body interference patterns. Nevertheless, floating hybrid systems generally face strong multi-body coupling and high control complexity, and their long-term operational reliability as well as responses to extreme sea states remain insufficiently validated.

From a historical perspective, research on WWHSs can be traced back to the Ocean Surge-driven Renewable Energy (OSPRED) project in the 1990s [131,135]. With the rapid development of OWTs in the early 2010s, research on WWHSs expanded [136–138]. The goal is to exploit the complementarity of wind and wave resources, where offshore wind provides high-capacity generation, and waves contribute more stable energy. Utilizing both resources is seen as an opportunity to accelerate technological development and harness numerous synergistic effects [90,139]. Design and analysis of WWHSs have been extensively studied, although only a few prototypes have undergone sea trials. Table 2 presents industry-driven hybrid initiatives, including demonstration projects, prototypes, and concept designs. To date, the most successful sea-tested hybrid platform are the P37 and P80 prototypes developed by Floating Power Plant (FPP), [140,141]. Similarly, companies such as Ocean Power Systems (DualSub concept [142]), Bombora Wave Power (InSPIRE project [143]), and Pelagic Power (W2Power concept [144]) initially focused on wave energy development but later proposed integrating their technology with FOWTs.

Based on the review of WWHS configurations and integration modes presented in this section, a clear technological evolution can be observed in recent years. The field has progressed from early co-located systems, where wind turbines and WECs were spatially independent and studies focused primarily on single-device performance and local energy capture, to structural integration, in which foundations and WECs are combined into unified designs. In this stage, OWCs or OB WECs coupled with fixed or floating foundations enable both load reduction and enhanced energy capture. More recently, research has advanced to system-level coupling, emphasizing platform responses, energy

interactions, and overall system stability, with multi-objective optimization emerging as a key focus, particularly for floating deep-water systems where it shows significant potential.

Table 2. Wind-wave hybrid system demonstration project.

Name	Wind Turbine Type	Wind Turbine Power Capacity (MW)	WEC Type	WEC Power Capacity (MW)	Status	Location
Poseidon P37 [140]	Semi-sub	3 × 0.011	Heaving	10 × 0.003	Sea test in 2012–2013	Denmark
P80 [141]	Semi-sub	4–10	Heaving	2–3.6	1:30 scale tested in 2022	Denmark
DualSub [142]	Semi-sub	2	Heaving	0.5	N/A	N/A
InSPIRE [143]	Semi-sub	8–12	Pressure	4/6	Scaled testing in 2022	University of Edinburgh
W2Power [144]	Semi-sub	2 × 3.6	Heaving	18 × 0.1	1:3 scale tested in 2008	Spain
NoviOcean [145]	Barge	3 × 0.05	Heaving	0.65	1:5 scale tested in 2022	Stockholm archipelago

From the perspective of system types, bottom-fixed hybrid systems demonstrate relatively high engineering maturity in nearshore and intermediate-depth waters, with research primarily targeting foundation–WEC structural compatibility and wave load mitigation. Floating systems, in contrast, exhibit greater potential in multi-degree-of-freedom coupling, array interference, and power smoothing characteristics. In terms of research content, the existing literature has largely covered the main system configurations and WEC types, but studies still focus predominantly on hydrodynamic response analysis and energy capture performance, relying mainly on numerical simulations and scaled experiments. Consideration of complex sea states, control–structure interactions, and practical engineering feasibility remains relatively limited.

Overall, the research reviewed in Section 3 outlines the development trajectory of WWHSs from conceptual proposals to integrated structural designs, providing a foundation for subsequent optimization studies aimed at improving system performance and engineering feasibility. Against this backdrop, it is necessary to further examine optimization strategies and methods from the perspectives of both technological design and spatial layout, which is the primary focus of Section 4.

4. Optimization of Hybrid Wind–Wave Energy Systems: Technologies and Layouts

In Section 3, this review systematically examined the current status and engineering characteristics of co-located, island, and WWHSs, focusing on their system integration forms. It is evident that as the degree of system integration increases, research emphasis has gradually shifted from conceptual validation toward system performance optimization and enhancement of engineering feasibility. Against this background, a key challenge for the practical implementation of WWHSs lies in achieving coordinated optimization of energy capture, structural safety, and economic efficiency under conditions of strong multi-device coupling. Building on the system classification presented in Section 3, this section further conducts a comprehensive analysis and comparison of existing studies from the perspectives of technological design and spatial layout. Unlike the local parameter optimization of individual devices, optimization in WWHSs exhibits clear multi-objective characteristics. The primary goals can be summarized as follows: improving overall energy

capture efficiency; reducing wave-induced loads on turbines and foundations; enhancing system motion responses and operational stability; and increasing life-cycle economic performance and engineering reliability. To address these objectives, existing research has gradually developed an optimization framework that links structural integration, energy conversion, and coordinated control and layout. This framework serves as a foundation for systematically evaluating multi-device interactions and guiding the design of efficient and resilient WWHSSs.

4.1. Technological Optimization

Technological optimization forms the foundation for achieving the four core objectives of WWHSSs. It is primarily advanced through three pathways: the integrated adaptation of foundation types with WECs, optimization of energy conversion mechanisms, and innovative design of hybrid foundations. These approaches have led to diverse and targeted technical solutions.

4.1.1. Integrated Design of Foundations and WECs

In fixed-bottom WWHSSs, configurations such as monopiles, jackets, and gravity-based foundations have been systematically reviewed in Section 3. Building on this, the present section focuses on the potential for structural and hydrodynamic optimization of these existing integration schemes, rather than on their configuration per se. Previous studies have shown that the rational integration of OWC or OB WECs with fixed foundations can not only enable wave energy extraction but also reduce wave-induced loads on the foundation through radiation damping and resonance effects. For instance, Zhou et al. [98] and Perez-Collazo et al. [100,146] demonstrated that the load reduction and power generation performance of OWC–monopile systems are highly sensitive to chamber geometry and turbine damping configurations, with optimized results varying significantly across different sea states. For OB WECs, related studies further indicate that adjusting the number of buoys, their spatial arrangement, and PTO parameters can achieve a certain degree of synergistic optimization between energy capture efficiency and structural response control [90,105]. As research has expanded from monopiles to jackets and CBF [108–110], optimization in fixed-bottom hybrid systems has gradually shifted from single-device performance evaluation toward system-level response management. However, due to substantial differences in device scale, operating conditions, and evaluation metrics among studies, a unified set of optimization criteria and performance assessment frameworks remains lacking. This limitation reduces the comparability of results and constrains the practical applicability of the findings in engineering contexts.

4.1.2. Power Conversion and Performance Enhancement

Based on the established integrated structures, improvements in energy conversion efficiency primarily depend on the optimization of the WEC's geometric parameters, motion characteristics, and PTO configuration. For OWC devices, Liu et al. [147] proposed an annular oscillating water column device (OWCD) integrated with a bottom-fixed wind turbine. Using analytical methods to simulate air–water interaction, they found that when the OWCD section width and draft are 1.0 and 1.5 times the monopile radius, respectively, wave energy capture efficiency can exceed 80% of the incident wave energy within a 2B width. The piston-mode resonance of water in the chamber is the key to maximizing efficiency. For OB WECs, existing studies generally indicate that their energy conversion performance is highly sensitive to structural parameters and layout configuration, with the number of buoys, geometric scale, and radial arrangement all significantly affecting the system's wave energy capture capability [27,107]. Ghafari et al. [130] highlighted the influence of device size on energy output, showing that a system composed of twelve

Wavestar units with a diameter of 5.575 m achieves approximately 12.85% higher power under omnidirectional wave conditions compared to a configuration of eighteen units with a diameter of 5 m.

Building on this, proper PTO parameter configuration is considered a key factor for achieving synergistic improvements in both energy conversion efficiency and system operational stability. Khatibani and Ketabdari [105] conducted system-level modeling of a coupled wind turbine and pitching WEC using time-domain BEM, revealing that the matching of PTO damping coefficients plays a critical role in maximizing wave energy capture. The hydrodynamic coupling between buoy arrays and monopile wind turbines exhibits notable variations under different PTO damping settings, and an appropriately configured damping scheme can substantially enhance overall power output [107]. It should be noted that these studies typically model PTO behavior using linear or equivalent damping assumptions. Such simplified models are practical for conceptual validation and parametric sensitivity analysis of WWHSs but exhibit clear limitations when capturing nonlinear dynamics, system responses under irregular sea states, and control potential. In particular, floating hybrid systems often display pronounced nonlinear characteristics due to multi-degree-of-freedom platform motions, device interactions, and irregular waves, which restricts the applicability of performance assessments based on linear damping assumptions.

Against this background, recent WEC studies have begun to adopt advanced control strategies to overcome the inherent limitations of traditional linear damping in terms of energy capture. For example, model predictive control [148] explicitly incorporates future wave excitation and system constraints to optimize PTO force output proactively, with equivalent control effects typically manifesting as frequency- and time-dependent optimal damping characteristics. Reinforcement learning-based control employs a data-driven mechanism to adaptively regulate complex nonlinear systems, thereby enhancing energy capture of individual WECs under broad-spectrum, irregular sea conditions [149]. Furthermore, incorporating nonlinear PTO models helps more realistically represent viscous effects, fluid dynamic resistance, and other nonlinear phenomena [150], improving the physical fidelity and response realism of the control strategy.

Although these advanced control strategies primarily target single WECs, their findings provide important insights for WWHSs. Notably, the introduction of advanced control strategies not only directly affects the instantaneous energy conversion efficiency of wave energy devices but can also alter the system's equivalent damping, stiffness, and added mass properties, thereby feeding back into the overall dynamics of the hybrid system. This implies that optimal buoy size, quantity, or spatial layout determined under simplified damping assumptions may no longer hold under more complex control frameworks, potentially impacting the optimal design conclusions for hybrid systems. In contrast, studies on control strategies for complete WWHSs remain limited [151], mainly because such systems are still at an early developmental stage, featuring strong multi-body coupling, complex control targets, and high engineering validation costs. A few existing works have begun to explore control strategies for hybrid systems, which can be categorized into three types: first, combining active feedback control with passive linear damping to evaluate system dynamics and power production using high-speed switching valves in series with the wind turbine [152]; second, two-state gain-scheduled damping control, which switches between two PTO damping configurations to suppress platform pitching [117]; and third, continuous gain-scheduled damping control, designed to reduce platform motion and wind turbine structural loads [153]. Studies indicate that two-state gain-scheduled damping control can reduce platform pitching by approximately 15%, while continuous gain-scheduled

damping control can lower tower-base fatigue loads by around 6%, demonstrating clear benefits in motion mitigation and structural safety.

Based on these developments, it is anticipated that multi-objective PTO control strategies that simultaneously optimize motion suppression and power maximization could further enhance the overall performance of WWHSSs. Consequently, advanced control strategies should not be regarded solely as operational-stage optimization tools but should be integrated into the system design and performance evaluation framework from the outset. Despite their demonstrated potential in theoretical studies, practical implementation of advanced control methods remains challenged by high computational complexity, real-time deployment difficulties, and strong reliance on accurate system models or training data. Balancing control performance improvements with engineering feasibility therefore remains a critical area for future research in WWHSSs.

4.1.3. Innovative Designs of Hybrid Foundation Concepts

As the level of integration in wind–wave hybrid systems continues to increase, foundation structures are required to satisfy the dual demands of multi-device support and dynamic coupling. To address the increased foundation load demands caused by multi-device integration, Ma et al. [154] proposed a monopile–steel-plate hybrid foundation (as shown in Figure 9). Finite element simulations verified that this scheme can achieve load optimization with the same mechanical response, avoiding an additional 17% embedment depth for the monopile and requiring only a 14 m diameter steel plate. Sensitivity analysis indicated that the system response at the mudline is most sensitive to variations in embedment depth and steel plate diameter. Although the hybrid foundation increases maximum lateral soil stress by up to 18%, it remains within a controllable range. This type of foundation innovation provides structural support for the integrated deployment of multiple energy devices, including offshore wind, wave energy, and hydrogen production systems. It has also contributed to the development of the concept of hybrid offshore renewable energy harvesting systems (HOREHSs), in which wind power serves as the core component. Such systems offer new engineering pathways for the integrated development of wind, wave, and energy storage technologies. From a broader perspective, foundation design is evolving from adaptation to individual devices toward coordinated support platforms for multiple energy sources, with design philosophies increasingly oriented toward system-level performance and life-cycle optimization.

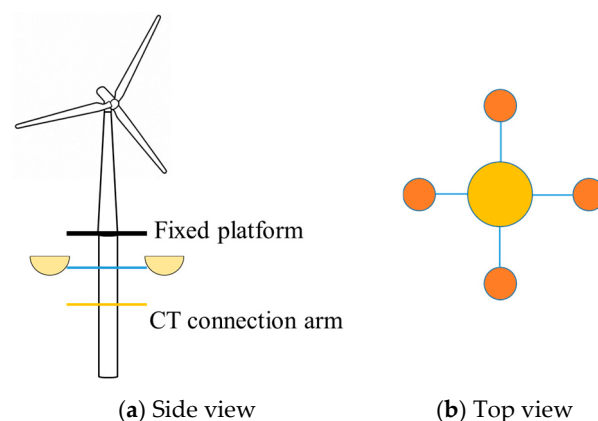


Figure 9. HOREHS diagram, adapted from [154].

4.2. Layout Optimization

Compared with technology integration, layout optimization places greater emphasis on system-level coordinated design. Its core objective is to harmonize energy capture,

structural response, and operational stability through the rational configuration of the number of WECs, their spatial distribution, and array arrangements.

4.2.1. Key Layout Parameters of Hybrid Wind–Wave Arrays

A large body of research indicates that the relationship between the number of WECs and overall system power output is strongly nonlinear. A moderate increase in the number of WECs can enhance energy absorption, whereas overly dense arrangements may degrade performance due to radiation and diffraction interference. Such configurations can also increase the effective added mass of the platform, thereby altering the natural frequencies and adversely affecting system stability. Ghafari et al. [28] studied the DeepCwind semi-submersible platform and found that as the number of Wavestar WECs increased, the ratio of full-wave-period power to response amplitude operator (RAO) rose synchronously, while the generation difference between 0° and 180° wave directions gradually decreased. For 6, 9, and 12 WEC configurations, the differences decreased by 32%, 26%, and 17%, respectively (schematic of the integrated system shown in Figure 10). Tian et al. [132] further confirmed that installing three WECs on a semi-submersible platform maximized pitch radiation damping, achieving an optimal balance between energy capture and motion suppression.

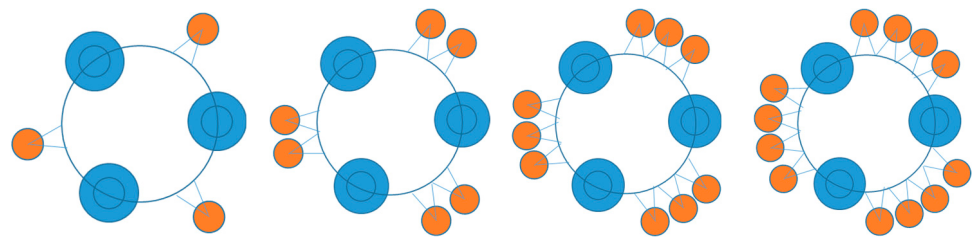


Figure 10. Integration of the DeepCwind semi-submersible platform with Wavestar WEC, adapted from [28].

Spacing and array arrangement directly affect hydrodynamic interference and energy capture efficiency. Regab et al. [155] used numerical simulations to determine that a staggered square layout was the optimal array. When longitudinal and transverse spacings were $5D$ and $4D$ (D is the rotor diameter), total system power increased by over 14.4%, while sea area usage decreased by 52.5%. De Backer et al. [156] compared 12 staggered-grid and 21 arranged-grid floating buoy arrays and found that diagonal optimization and individual optimization strategies increased power output by 16–18%, significantly outperforming single-buoy control schemes. These findings indicate that layout optimization affects not only energy production but also has a direct impact on the dynamic characteristics of the platform.

4.2.2. Layout Optimization Algorithms and Simulation Tools

With the rapid growth of computational capability, multi-objective optimization algorithms have become essential tools for layout design. GPU-accelerated methods, multi-objective differential evolution, and intelligent heuristic algorithms have demonstrated clear advantages in the optimization of WWHSs [157,158]. At the same time, to address the high computational cost associated with wave wake modeling, the introduction of preprocessing techniques and reduced-order modeling has significantly improved optimization efficiency [159].

In terms of numerical simulation, Xu et al. [160] developed the multiphase solver overWaveIsoFoam, which integrates the isoAdvector algorithm with overset mesh technology. This framework enables accurate simulation of the hybrid system consisting of the

DeepCwind platform, an internal oscillating-body WEC, and an external Wavestar device, providing an efficient tool for optimizing the layout of both inner and outer WECs, as illustrated in Figure 11. Such advances make high-fidelity modeling of complex integrated systems feasible [160] and offer a reliable physical basis for layout optimization.

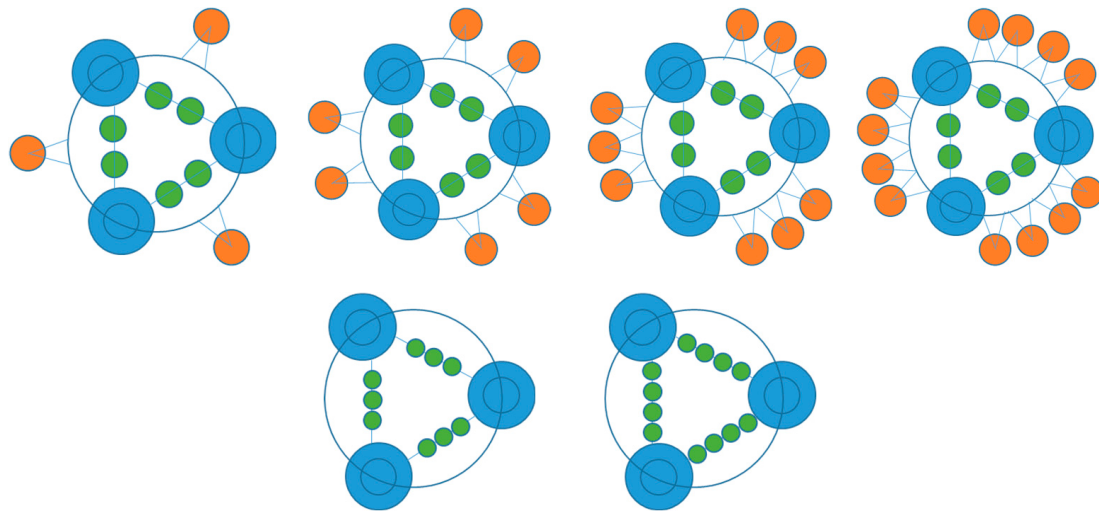


Figure 11. Integration of semi-submersible platform with multiple WECs (Green: OB WEC, Orange: Wavestar, Blue: semi-submersible platform), adapted from [160].

4.2.3. Platform Type Adaptation Layout Strategy

The dynamic characteristics of different floating platforms vary substantially, which makes platform adaptability a critical requirement in layout optimization. For barge-type FOWTs, Ding et al. [20] proposed the IFES model, showing that the directional integration of WECs is crucial for suppressing platform rotational motion. When eight WECs are symmetrically distributed, the platform's roll motion amplitude is reduced by up to 71.52%. Longitudinal WECs dominate energy capture and significantly decrease the tower base roll moment, though increasing WEC numbers may raise the pitch moment due to nonlinear interactions (schematic of the integrated system shown in Figure 12).

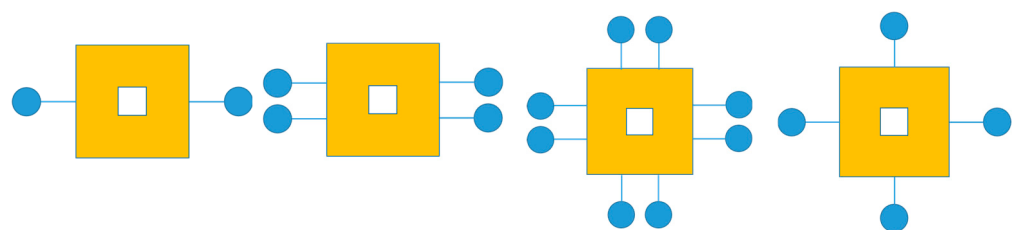


Figure 12. IFES model composed of barge FOWT and multiple oscillating WECs, adapted from [20] (The yellow part represents the barge FOWT, and the blue circle is the WEC).

For semi-submersible platforms, layout optimization emphasizes multi-parameter coordination. Jin et al. [161] studied the DeepCwind platform integrated with Wavestar WECs and identified a 30° enclosure angle and 22.87 m arm projection as optimal parameters (schematic shown in Figure 13). Xu et al. [160] applied hierarchical optimization to determine a hybrid layout of 12 internal OBWECs and 15 external Wavestar devices, which substantially reduced surge, pitch, and heave motions and enhanced wave diffraction effects. Hu et al. [126] investigated semi-submersible platforms with multiple oscillating WECs, using potential flow theory and frequency-domain viscous corrections to precisely match WEC size and layout to specific sea states, while also mitigating platform pitch motion (schematic shown in Figure 14).

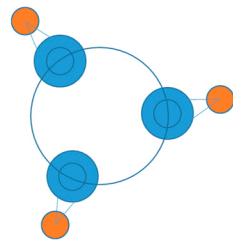


Figure 13. Integration of the DeepCwind platform with Wavestar WEC, adapted from [161] (The yellow part represents the WEC, and the blue circle is the DeepCwind platform).

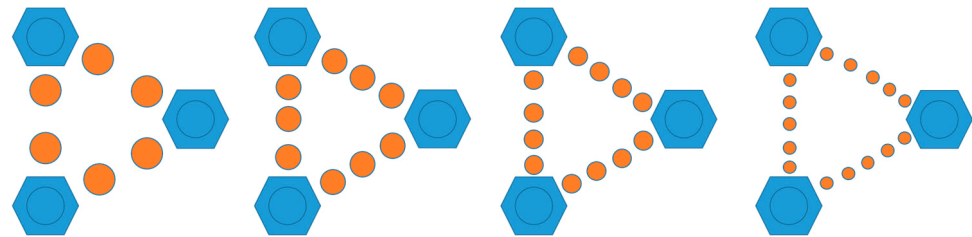


Figure 14. Semi-submersible platform-multiple heave WEC system, adapted from [126] (The yellow part represents the WEC, and the blue part is the Semi-submersible platform).

The optimization of WWHSSs has developed into a coordinated framework integrating technology and layout design. Technical optimization focuses on foundation–WEC compatibility, energy conversion efficiency enhancement, and hybrid foundation innovation. Layout optimization achieves multi-objective balance through parameter tuning, algorithmic support, and platform adaptation. Existing studies have demonstrated that the integration of OWC and buoy WECs on monopile and multiple foundation types possesses engineering application potential. Layout strategies such as staggered grids and symmetric distributions, combined with algorithmic tools like GPU-accelerated optimization and wave wake pre-processing, significantly improve system performance. Future research should further investigate coupling mechanisms under complex sea states and promote collaborative layout optimization of multiple WEC types, supporting comprehensive improvements in lifecycle economic efficiency and system stability.

5. Discussion

5.1. System-Level Performance Analysis

Existing studies consistently show that effective technological integration and well-designed array layouts are key pathways to enhancing the overall performance of WWHSSs. System-level performance is mainly reflected in three aspects.

(1) Energy capture efficiency. By integrating different types of WECs on fixed foundations or floating platforms, hybrid systems can achieve the coordinated utilization of wave and wind energy [96,98,100]. Previous studies demonstrate that both OWC devices and OB WECs can significantly increase system power output when integrated with various wind turbine foundations. It is worth noting that system-level energy capture efficiency depends not only on the performance of individual devices but also on array configuration and the coupled hydrodynamic interaction between wind turbine foundations and WECs [28,131].

(2) Structural loads and platform motion response. A large body of research indicates that optimizing the spatial distribution and array form of WECs can effectively suppress key motion responses of floating platforms, such as pitch and roll, while reducing wave-induced loads [90,98,104]. For example, staggered layout [155] has been shown to regulate platform motions and promote a more balanced load distribution. Such optimization

strategies improve structural safety and provide important support for extending the fatigue life of the system.

(3) Stable power output. The combination of multiple devices and array optimization not only enhance the efficiency of energy capture but also significantly improve the temporal smoothness of power output [162], reducing the impact of wind-wave power fluctuations on the stability of grid operation and providing a key guarantee for engineering applications.

Overall, system-level optimization has evolved from an early focus on individual device parameters toward a multi-objective approach that jointly enhances energy capture, load mitigation, and system stability. This shift provides a solid theoretical basis for subsequent assessments of engineering feasibility and integrated system design. A summary of recent studies on hybrid systems is presented in Table 3.

Table 3. Recent studies on WWHs.

No.	Wind Turbine	WEC	Main Content	Reference
1	Monopile	OWC	PTO damping significantly affects hydrodynamic efficiency, with each wave condition having an optimal PTO damping value that maximizes the CWR. The optimal opening ratio is approximately 1.25%, resulting in a maximum CWR of 0.63.	[95]
2	Monopile	OWC	The damping coefficient is the primary factor affecting the capture width ratio. Run-up is higher on the OWC chamber face than on the monopile and increases with both wave steepness and damping coefficient. Under irregular waves, maximum run-ups are 1.5–2 times larger than in regular waves and show a stronger dependence on wave steepness.	[96]
3	Monopile	OWC	The inclusion of an internal cylinder produces broad peaks in the capture factor at higher frequencies. The optimal skirt opening angle for maximizing power extraction is the symmetric configuration ($\theta_1 = 2\pi/3$; $\theta_2 = \pi/2$).	[97]
4	Monopile	OWC	The presence of the OWC chamber reduces both the horizontal force and overturning moment on the monopile.	[98]
5	Monopile	OWC	In certain wave conditions, the wave forces on the OWC and the monopile mutually balance, resulting in a near-zero net force on the integrated system.	[99]
6	Monopile	OWC	The hybrid device reflects 5–66% and transmits 3–45% of incident wave power. Optimal performance occurs with a turbine damping corresponding to a 0.5% orifice, with a second peak at 1.0%. Resonance peaks appear at $T = 6$ s and $T = 9$ s, with a broad high-performance region between $T = 8$ s and 11 s.	[146]
7	Monopile	OWC	Peak efficiency occurs during piston-mode resonance of the water column. When the OWC cross-section width equals the monopile radius ($B = R$) and its draft is $1.5R$, the device absorbs over 80% of the incident wave energy across a width of $2B$.	[147]
8	Jacket	OWC	The maximum value of CWR is about 13%, with average values between 4% and 7%.	[100]
9	Monopile	Semi-immersed buoy	Compared to an isolated WEC array without a monopile, the integration with a monopile enhances the overall power absorption of the hybrid array across a broad frequency range. Specifically, the two front WECs show a 15% increase in power, while the two rear WECs experience an 8% reduction due to shielding. Additionally, the buoy reduces wave loads and overturning moments on the monopile by 25% and 32%, respectively. However, the total horizontal wave force on the combined hybrid system exceeds that on a standalone monopile.	[104]

Table 3. Cont.

No.	Wind Turbine	WEC	Main Content	Reference
10	Monopile	Hollow annular buoy	The buoy reduces wave loads and overturning moments on the monopile by 25% and 32%, respectively, while the monopile also reduces horizontal loading on the WEC. However, the total horizontal wave force on the integrated system exceeds that on a standalone monopile foundation.	[27]
11	Monopile	Hollow annular buoy	In the MWWC system, the WEC performs optimally at a wave period of approximately 10 s, while the NREL 5-MW wind turbine contributes the dominant share of the total power output.	[102]
12	Monopile	Segmented buoy	A segmented buoy integrated with a monopile absorbs about 1.3 times more power than an annular buoy under a Coulomb-type PTO and shows superior performance at shorter wave periods; this advantage remains for certain PTO coefficients under a linear PTO model.	[107]
13	Monopile	Segmented buoy	By adding WECs to monopile, the hybrid system can produce 26.44% more renewable energy than the monopile offshore wind turbine.	[105]
14	CBF	Cylindrical buoy	Compared with the single CBF, the CBF-OB WWHS can reduce the wave run-up by about 0–60% and the wave pressure by about 0–40% at the position of 0–135°. At 135–180°, the wave run-up can increase by about 0–40%, and the wave pressure can increase by about 0–50%. The CBF-OB WWHS can significantly improve the absorption efficiency of the buoy, which is about 1.5 to 4.0 times higher than that of the single buoy.	[109]
15	Jacket	Cone bottom cylindrical buoy	Compared to the heave-type WEC integrated with a jacket, the swing-type WEC exhibits higher motion velocities, greater support reaction forces, and larger connection loads, thereby exerting a more significant influence on the jacket structure. Additionally, in terms of power capture, the swing-type WEC demonstrates clearly superior average hourly power generation.	[108]
16	Monopile	Cone bottom cylindrical buoy	When monopile is combined with large dense arrays of WECs to form a WWHS, it will have a destructive impact on the overall energy extraction. Such effects are more negative under high-frequency waves.	[110]
17	Spar	OWC	Compared to a standalone 5 MW FWT, the power of the hybrid system has increased by 9%. By eliminating the independent WEC mooring lines and infrastructure costs, the WEC leveled cost of energy is reduced by 14% and the equivalent tower root stress of the FWT during its lifetime is reduced by 23%.	[111]
18	Spar	OWC	The large number of OWC WECs increases the generated power, and reduces the dynamic response of the spar platform.	[112]
19	Barge-based floating platform	OWC	The barge platform with an OWC effectively reduces pitch and fore-aft tower-top oscillations under regular waves with periods between 6.4 s and 12.25 s. In contrast, a single barge platform performs better for wave periods of 12.25 s to 20 s. For the remaining wave periods, there is no significant difference in performance between the two platforms.	[114]
20	Barge-based floating platform	OWC	The barge equipped with OWC performs better than a single barge. With the period of 10 s, the barge with OWC significantly reduced the pitch angle by 30.8% and fore-aft displacement by 25% compared to the single barge system.	[115]

Table 3. Cont.

No.	Wind Turbine	WEC	Main Content	Reference
21	Semi-sub	OWC	The platform exhibits a lower response in fully or partially open chambers. When the chamber is open or partially open, the influence of the PTO on the platform's dynamic response is limited, indicating that the normal operation of the OWC has a limited impact on the platform's dynamics.	[116]
22	Semi-sub	OWC	A semisubmersible is usually designed with a small motion to prevent the wind turbine from becoming much more rigid in strength. However, the high efficiency of wave energy conversion requires a large motion of the platform. Instead of pursuing the wave energy conversion efficiency, an increase in damping effect or help in reducing the wave exciting force on semisubmersible would be the primary consideration of the integration.	[117]
23	Semi-sub	OWC	The introduction of the oscillating water column can not only capture wave energy but also reduce the heave, roll and pitch responses, especially for long waves $kh \leq 2.0$, $kh \leq 1.4$ and $kh \leq 1.76$, respectively. The maximum reduction in heave, roll and pitch are 35%, 55.4% and 13.8%, respectively.	[118]
24	Spar	Hollow annular buoy	As the damping increases, the surge, pitch, mooring rope line remain unaffected, while spar heave and torus heave motions tend to be more similar, the relative heave motion weakens, and the average absorbed wave power does not significantly increase. Compared with the situation without wind, the wind causes larger deviations in the average wave surge and pitch motions. The influence of wind on wave energy absorption can be ignored.	[23]
25	Spar	Hollow annular buoy	The presence of WECs and tidal turbines will reduce the bending moments of the tower base fore-aft but increase the mooring tension.	[119]
26	Spar	Hollow annular buoy	In the rated operating condition, the pitch amplitude of the combined concept is 31.5% less than that of the FOWT. At the same time, the torus-shaped WECs hardly affect the power performance of the wind turbine. The combined concept provides an additional contribution of wave energy, which is about 11.4% of the annual power production in the rated operating case.	[162]
27	Spar	Cone bottom cylindrical buoy	The smaller the distance between the spar and the WECs, the smaller the power generated, attributed to the strong fluidic interaction effect. If a large number of WECs are used, the distance between the spar and the WECs should be increased to avoid the negative impact of the interaction effect on the output power.	[120]
28	TLP	Hollow annular buoy	In coupled wind-wave conditions, wind loads dominate the mean surge response, while wave loads govern the standard deviation and peak responses. Under rated wind conditions, power output is mainly from the wind turbine and no WEC water exit or entry occurs. Under maximum operational seas, water exit and entry of the WEC floater may occur when the significant wave height reaches 6 m.	[122]
29	STLP	Cone bottom cylindrical buoy	By arranging 8 WECs in a circular and concentric manner around the STLP, the motion of the WECs will be minimally hindered. At this time, the proportion change range of the hydrodynamic coefficient is the smallest, the power output is relatively stable, and it can absorb the maximum wave energy.	[124]

Table 3. Cont.

No.	Wind Turbine	WEC	Main Content	Reference
30	Semi-sub	Hollow annular buoy	With the increase in the number of WECs, the added mass of surge and pitch of the semisubmersible will be larger. The effect of the number of WECs on radiation damping surge and pitch of the semisubmersible is significant in the high frequency range. Radiation damping of pitch motion of the semisubmersible with three WECs has the largest value.	[132]
31	Semi-sub	Cylindrical buoy	The addition of WECs reduced the maximum horizontal force and pitch moment on the platform, whereas the maximum vertical force increased due to the increasing power take-off force, especially at low frequencies.	[126]
32	Semi-sub	Cylindrical buoy	When the platform and WEC are in synchronous mode, the power of a single WEC can be increased by up to 41.4%, and the total power can be raised to 26.7%. The heave motion of the platform also increases. Out of the vicinity of the synchronized mode frequency, the WECs have a small impact on the surge motion and pitch motion of the platform, whereas reducing its resonant heave motion at the natural frequency.	[133]
33	Semi-sub	Cylindrical buoy	Compared to the wind turbine, the amplitude of heave and pitch motions of the combined concept is reduced due to the generated damping from the WECs. An increase in motion amplitude of the WECs causes an increment in the extraction of energy from ocean waves.	[134]
34	Semi-sub	Cone bottom cylindrical buoy	Compared with a single floater, the array undertakes higher efficiency at low wave periods. Because the tested wave period is far away from resonance period of the platform, pitch, heave and surge are almost increased at all periods.	[127]
35	Semi-sub	Cone bottom cylindrical buoy	The experimental results reveal overall that the addition of WECs on the floating platform may have desirable or undesirable effects; thus, there are contradicting effects on heave and pitch motions in the operational and survival modes.	[128]
36	Semi-sub	Hemispherical bottom buoy	Reactive control generally worsen the platform motion responses, while spring–damping control is able to mitigate the pitch motion to certain extent. Regarding power output, reactive control leads to the highest wave power generation, almost twice as much as that of spring–damping.	[129]
37	Semi-sub	Hemispherical bottom buoy	Adding wave absorbers to the 5-MW braceless semi-submersible FOWT leaves surge motion nearly unchanged, while significantly reducing heave and pitch responses. Although individual wave absorbers generally produce less power than a standalone device, WS1 exceeds the single-WS power at wave periods above 8 s due to diffraction effects from the platform side columns.	[130]
38	Semi-sub	Cylindrical buoy and Hemispherical bottom buoy	The hybrid system, incorporating 12 inner OBWECs and 15 outer Wavestars, achieves an optimal layout with notable reductions in surge, pitch, and heave motions compared to the standalone DeepCwind platform. The integration of diverse WEC types increases mean mooring loads, though these remain within acceptable and predictable limits.	[160]

5.2. Technological Trends and Methodological Innovations

Recent advances reveal several representative trends in both technological pathways and analytical methods for WWHSs.

(1) Continuous innovation in foundation–WEC integration. Integration schemes involving monopoles [100], CBFs [109], and semi-submersible platforms [111] are becoming increasingly mature. Coordinated operation of multiple devices not only improves overall

power output but also effectively reduces local load peaks, achieving a dual optimization of structural safety and energy utilization efficiency.

(2) Rapid development of array layout and spatial coupling optimization. Array spacing, configuration, and overall arrangement directly influence wave interference effects and energy capture efficiency [155]. In recent years, GPU-accelerated multi-objective optimization algorithms [156] and wave-wake pre-processing techniques [160] have been widely applied in layout design. These approaches provide powerful tools for the efficient analysis of complex array systems.

(3) The gradual development of multi-scale analysis frameworks. Methods for analyzing responses from local components to the coupled motions of entire platforms are continuously being refined. By integrating high-fidelity numerical simulations, scaled model experiments, and engineering experience, researchers are progressively establishing a more reliable system performance prediction framework, which provides critical support for the engineering design of complex hybrid systems.

5.3. Research Gaps and Challenges

Although research on WWHSs has achieved notable progress, several critical issues remain to be addressed as the field moves toward engineering deployment and large-scale application.

(1) Lack of a unified system performance evaluation framework. Most existing studies still rely on single power indicators or local load responses as optimization objectives. A comprehensive multi-objective evaluation framework that balances energy efficiency, structural safety, and operational stability has yet to be established. This limitation hampers cross-comparison among different system concepts and restricts the effective transfer of research outcomes into engineering practice.

(2) Insufficient investigation of extreme sea states and long-term reliability. Current work is largely focused on performance under regular waves or limited combinations of operating conditions. Systematic studies addressing responses to extreme sea states, long-term fatigue behavior, and full life-cycle economic performance remain relatively scarce. As a result, available evidence is still inadequate for fully supporting engineering decision-making.

(3) Limited systematic understanding of cross-system and multi-type WEC coordination. Most optimization efforts concentrate on single WEC types or individual platform configurations. The synergistic mechanisms among different systems and multiple WEC types, particularly their potential contributions to power smoothing and system stability, have not yet been explored within a mature and coherent research framework.

(4) Insufficient validation through engineering applications. The majority of existing results are still confined to numerical simulations or scaled experiments. Long-term operational data from large-scale demonstration projects are scarce, leading to persistent uncertainties in assessments of system reliability, maintainability, and economic feasibility.

In summary, research on WWHSs has progressed from an initial stage of single-device optimization to a new phase characterized by system-level coordinated optimization. Technological integration, array layout design, and multi-scale analytical methods have provided a strong theoretical foundation for performance enhancement. However, significant gaps remain in unified evaluation criteria, extreme-condition and long-term reliability analysis, cross-system coordination mechanisms, and full-scale field validation. Future studies should therefore focus on comprehensive system-level optimization, life-cycle reliability assessment, and engineering feasibility verification, in order to support the steady transition of WWHSs toward large-scale and practical application.

6. Conclusions and Suggestions for Future Research

6.1. Conclusions

In recent years, both offshore wind and wave energy technologies have achieved significant progress. The engineering adaptability of wind turbine foundations has steadily improved, while wave energy devices have seen continuous enhancements in energy capture efficiency and reliability. Against this technical backdrop, WWHSs leverage structural sharing, resource complementarity, and dynamic coupling, emerging as a key direction for integrated marine energy development. A review of current advances indicates:

(1) OWT foundation technology is progressing from nearshore to deep and ultra-deep waters. Fixed foundations are relatively mature for nearshore applications, with future development focusing on structural lightweighting, adaptability to complex geotechnical conditions, and improved installation efficiency. For floating foundations, semi-submersible, TLP, and Spar configurations collectively form the main technical pathways for deep-water wind energy, with semi-submersibles being the mainstream choice in demonstration projects due to strong stability and broad water depth adaptability. However, structural reliability, fatigue life assessment, and large-scale cost remain key technical challenges in deep-water environments.

(2) Wave energy technology is developing along multiple parallel pathways. Oscillating-body devices, particularly point absorbers, are a research focus due to their compact structure and adaptability, but engineering deployment is constrained by extreme sea-state loads, corrosion, and biofouling. OWC technology is relatively mature but depends on specific shoreline topographies. Overtopping devices can smooth power output fluctuations, yet their large-scale structures pose deployment challenges. Overall, all three device types face limitations in cost, reliability, and environmental adaptability, which restrict large-scale commercialization.

(3) Hybrid wind–wave system technologies are being explored along diverse approaches. Co-located systems offer flexible deployment and low engineering risk, making them suitable for nearshore demonstrations, though wind–wave coupling effects are limited. Island-type systems (artificial or floating) promote intensive marine space utilization and are a key direction for deep-water multi-energy integration, but they incur high construction costs and increased system complexity. Hybrid systems enhance energy capture and reduce structural loads through structural integration and dynamic coupling, representing the pathway with the greatest industrialization potential.

(4) System performance improvement relies on the coordinated advancement of structural integration and layout optimization. Foundation–WEC integrated designs enable foundation sharing and load synergy. Through precise PTO damping adjustment and hybrid foundation innovation, energy conversion efficiency and structural stress performance can be further optimized. Layout optimization has gradually formed a multi-objective framework of “parameter modeling—intelligent algorithms—platform scenario adaptation.” By adjusting WEC numbers, spacing, and platform-specific layouts, a balance between energy capture, structural stability, and spatial efficiency can be achieved. Nonetheless, challenges remain in complex sea states, multi-scale dynamic coupling, and real-time adaptability.

Overall, WWHSs are accelerating from conceptual design and laboratory validation toward small-scale demonstration applications. However, industrial deployment and large-scale commercialization still require breakthroughs in foundation–WEC integration, fluid–structure interaction dynamics, intelligent control strategies, lifecycle cost optimization, and grid compatibility.

6.2. Future Research

To address current research gaps and technical bottlenecks, and to advance WWHs from experimental validation to commercial deployment, future studies should focus on the following directions:

(1) In-depth investigation of structural integration and hydrodynamic coupling mechanisms. Develop refined models of the coupled response between wind turbines and WECs, particularly considering multi-field interactions of wind, waves, and currents on floating platforms. Conduct full-scale or large-system evaluations under realistic sea conditions to capture load spectra, structural responses, and fatigue damage, thereby reducing discrepancies between numerical simulations and practical engineering. These studies will provide reliable foundations for subsequent design methods and standard frameworks.

(2) Collaborative optimization design for multi-energy coupled systems. Future research should establish multi-objective optimization frameworks that account for both wind and wave energy characteristics, encompassing key factors such as foundation type, WEC configuration, layout, and scale parameters. For monopile, jacket, semi-submersible, and Spar foundations, optimal coupling strategies with point absorbers, OWCs, and over-topping devices should be explored to achieve system-level coordination between energy capture, structural loading, and cost.

(3) Deep integration of intelligent control and digital twin technologies. Intelligent control strategies should be incorporated into PTO systems and platform motion management to achieve efficient real-time adaptation to changing sea states. System-level digital twins enabling virtual-to-physical mapping can support structural health monitoring, fault diagnosis, lifespan prediction, and O&M optimization, representing a critical pathway for improving long-term reliability and economic performance of hybrid systems.

(4) Lifecycle cost modeling and reliability-based design frameworks. Develop LCOE analysis frameworks tailored to WWHs to quantify cost-saving potential through structural sharing, foundation reuse, and coordinated operation. Strengthen reliability assessments under long-term environmental effects, including corrosion, extreme sea states, and biofouling, and promote maintainable and modular design strategies. Multi-scenario demonstration projects under nearshore fixed and deep-water floating conditions are recommended to validate the feasibility of full-process technologies and commercial models.

(5) Integration of ecological friendliness with engineering design. Investigate the interaction mechanisms between WWHs and the marine ecosystem to establish cross-scale assessment methods balancing energy development and ecological protection. Optimizing device morphology, foundation structures, and array layouts can reduce disturbances to marine habitats, hydrodynamic conditions, and sediment processes, promoting coexistence of engineering systems and ecological integrity.

Overall, breakthroughs in these directions will lay the foundation for large-scale deployment and commercialization of WWHs, advancing marine renewable energy toward an efficient, safe, economical, and environmentally sustainable utilization stage.

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Abbreviations

WWHS	Wind–wave hybrid system
OWT	Offshore wind turbine
FOWT	Floating offshore wind turbine
CBF	Composite bucket foundation
OB	Oscillating buoy
PTO	Power take-off
WEC	Wave energy converter
RAO	Response amplitude operator
UN-SDG	United nations sustainable development goal
TLP	Tension-leg platform
OWC	Oscillating water column
PDA	Peripherally distributed array
UDA	Uniformly distributed array
NDA	Non-uniformly distributed array
OSPNEY	Ocean surge-driven renewable energy
OWCD	Oscillating water column device
BEM	Boundary element method
HOREHS	Hybrid offshore renewable energy harvesting system

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