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Review

The Energy Conversion and Coupling Technologies of Hybrid Wind–Wave Power Generation Systems: A Technological Review

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Abstract: Based on the mutual compensation of offshore wind energy and wave energy, a hybrid wind–wave power generation system can provide a highly cost-effective solution to the increasing demands for offshore power. To provide comprehensive guidance for future research, this study reviews the energy conversion and coupling technologies of existing hybrid Wind–wave power generation systems which have not been reported in previous publications. The working principles of various wind and wave energy conversion technologies are summarised in detail. In addition, existing energy coupling technologies are specifically classified and described. All aforementioned technologies are comprehensively compared and discussed. Technological gaps are highlighted, and future development forecasts are proposed. It is found that the integration of hydraulic wind turbines and oscillating wave energy converters is the most promising choice for hybrid wind–wave power extraction. DC and hydraulic coupling are expected to become mainstream energy coupling schemes in the future. Currently, the main technological gaps include short their operating life, low energy production, limited economic viability, and the scarcity of theoretical research and experimental tests. The field offers significant opportunities for expansion and innovation.

Keywords: offshore wind energy; wave energy; hybrid energy extraction; energy coupling; energy conversion

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1. Introduction

With the intensity of the energy crisis, the international structure of energy has gradually shifted from traditional fossil fuels to clean, renewable energy sources [1]. Ocean renewable energy sources, such as offshore wind, wave, and solar energies, are not only abundant but also widely distributed, garnering global attention [2,3]. Europe currently has the world's largest installed ocean energy capacity, which is expected to increase to 188 GW by 2025 [4]. Countries such as the UK, Denmark, France, Germany, and Belgium have implemented lasting policies to promote the development of ocean renewable energy [5,6]. In alignment with this global trend, the Chinese government has committed to ocean energy development and its utilisation through significant national strategies, including the '12th Five-Year Plan' in 2012 and the '13th Five-Year Plan' in 2020. These strategic initiatives underscore the heightened focus on expanding China's ocean energy capabilities and increasing its investment in renewable energy development [7].

Compared to other ocean energy sources, offshore wind energy is considered the most promising because of its high energy density and well-established technological development. One of the most famous demonstration projects of this is WindFloat Atlantic, which is located 20 km off the coast of Viana do Castelo, Portugal. It is considered to be the world's first semi-submersible floating wind farm and was the first floating wind farm in continental Europe [8]. Ambitious plans have been formulated to increase wind farms' capacity from 12 GW in 2020 to 300 GW by 2050 in the EU and from 5 GW in 2020 to 200 GW by 2050 in China [9,10]. However, the inherent randomness and intermittence of offshore wind energy inevitably lead to large power fluctuations in the terminal power system, resulting in increased maintenance and balance costs [11–13]. To address this challenge, various multi-energy complementary power generation schemes have been proposed that integrate offshore wind energy with other ocean energy sources [14–19]. Among these, the combined wave–wind power generation system is considered to be the best option due to its economic efficiency and technical feasibility [20–23].

Offshore wind and wave energies can compensate for each other in time and space, showing a certain synergy between the wave peaks that follow wind peaks [24,25]. The combined exploitation of offshore wind energy and wave energy has several advantages, including enhanced energy yields, improved predictability, smoothed output power, cost-effectiveness, and environmental benefits [26–28]. In recent years, numerous countries have conducted comprehensive resource assessments of offshore wind and wave energy to develop combined wind–wave power generation systems [29–37]. Based on their foundation and layout, combined wind–wave power generation systems can be classified as follows [26]: co-located (Figure 1a), island systems (Figure 1b), and hybrid systems (Figure 1c). Co-located systems and island systems consist of large offshore wind farms and wave energy converter arrays on independent foundations in the same marine area [38,39]. The major technologies of these systems are relatively mature and many demonstration projects have been implemented globally [40–44]. Hybrid systems, identified as a new research hotspot in recent years, combine offshore wind turbines and wave energy converters on the same foundation [45]. Compared with co-located and island systems, hybrid systems have the advantages of a smaller size, lower manufacturing and maintenance costs, and higher energy utilisation efficiency per unit area [46]. The most renowned hybrid wind–wave system is part of the WindFloat Atlantic project. This system has three floating wind turbines with a total capacity of 25 MW and a wave energy converter developed by the Portuguese company WavEC Offshore Renewables [47]. The wind turbines are anchored using advanced floating platforms that allow them to operate in deeper waters. The wave energy converter, which is integrated into the same floating platform as the wind turbine, captures energy from ocean waves.

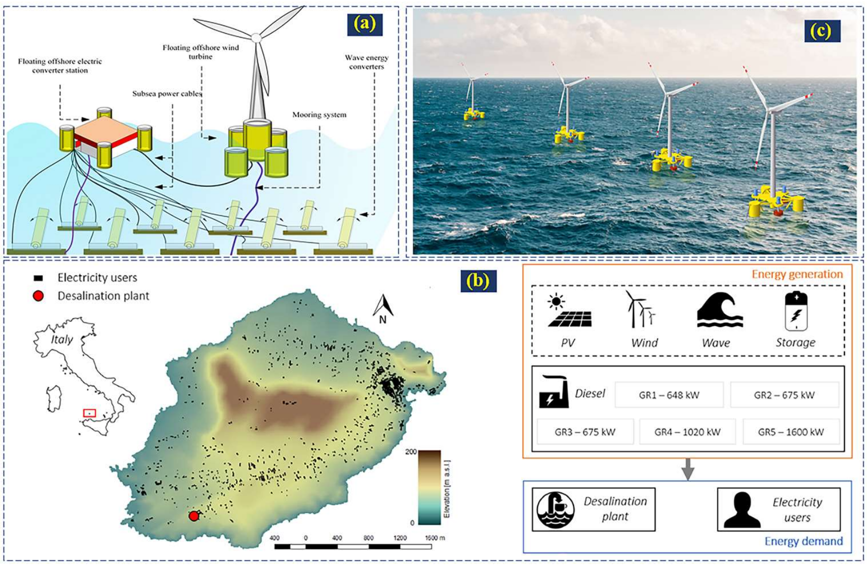

Figure 1. Classification of combined wind–wave power generation systems: (**a**) Co-located system. Reproduced with permission from [48], Elsevier (Amsterdam, The Netherlands), 2022. (**b**) Island system. Reproduced with permission from [49], Elsevier (Amsterdam, The Netherlands), 2022. (**c**) Hybrid system. Reproduced with permission from [50], Elsevier (Amsterdam, The Netherlands), 2024.

Although hybrid wind–wave systems have recently become a research hotspot, studies on hybrid wind–wave systems are limited. The current research is primarily categorised into three groups: (i) potential assessments of hybrid wind–wave explorations [31,51–54]; (ii) hydrodynamic studies on substructures such as wave energy converters, wind turbines, and floating or bottom-fixed platforms [55–62]; and (iii) the power preferences of their integrated systems [63–67]. Several reviews have been conducted on these research areas in recent years. Qiang et al. assessed the potential of hybrid wind–wave exploration in Australia [31]. Iglesias et al. classified combined wind–wave systems and reviewed WEC technologies [26]. Hongda et al. provided a comprehensive review, which included global assessments of wind energy and wave energy resources and the foundation structures of hybrid wind–wave systems [45]. McTiernan and Sharman reviewed the types of hybrid wind–wave systems and discussed their advantages and disadvantages [68]. Subbulakshmi et al. summarised the state-of-the-art experimental and numerical methods used for the dynamic analysis of hybrid wind–wave systems [69]. Anthony et al. reviewed industrial projects for hybrid wind–wave energy extraction [70]. However, there are no publications that provide a systematic review of the energy conversion and coupling technologies of existing hybrid wind–wave systems.

The effectiveness of a hybrid wind–wave power generation system relies heavily on its seamless integration of energy conversion and coupling technologies. This paper presents a comprehensive review of the energy conversion and coupling technologies of existing hybrid wind–wave systems. A major contribution of this study is that it provides an in-depth analysis of the current state of the research in this field, emphasising the importance of efficient energy conversion and coupling strategies. The remainder of this paper is organised as follows: In Section 2, the energy conversion technologies of existing hybrid wind–wave systems are illustrated. Section 3 classifies and analyses the energy coupling technologies of existing hybrid wind–wave systems. Section 4 discusses these technologies, elaborates on technological gaps, and forecasts the development of these technologies. Finally, the conclusions are presented in Section 5.

2. Energy Conversion Technologies

The development of hybrid wind–wave systems has benefited significantly from the technological advancements in offshore wind turbines and wave energy converters. These systems combine offshore wind turbines and wave energy converters on the same foundation. This section presents a summary of the wind and wave energy conversion technologies utilised in existing hybrid wind–wave systems. The classification of these technologies is illustrated in Figure 2.

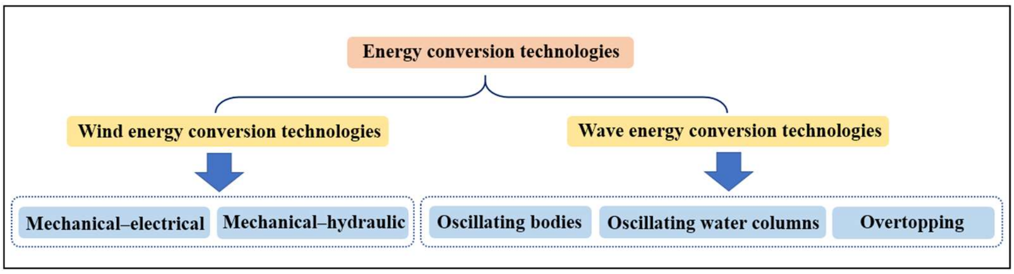

Figure 2. Classification of the energy conversion technologies utilized in existing hybrid wind–wave systems.

2.1. Wind Energy Conversion Technologies

Hybrid wind–wave systems utilise the same foundation structures as traditional offshore wind turbines, comprising both floating and bottom-fixed foundations. The wind energy conversion technologies employed in existing hybrid wind–wave systems can be divided into two types: mechanical–electrical and hydraulic–electrical.

2.1.1. Mechanical–Electrical Schemes

Mechanical–electrical wind energy conversion schemes are widely employed in hybrid wind–wave systems. Over the past decade, numerous demonstration projects have been conducted, such as Wave Treader [71], W2Power [72], Floating Power Plant AS [73], and WindWaveFloat [74]. In addition, a considerable number of conceptual hybrid wind–wave systems employing a mechanical–electrical wind energy conversion scheme have been proposed over the past three years [65,67,75–77]. A typical mechanical–electrical wind energy conversion scheme is depicted in Figure 3. The blades are driven by wind, and their pitch angles and rotational speeds are continually adjusted to optimise their wind energy utilisation efficiency. The generator converts wind energy into electrical energy.

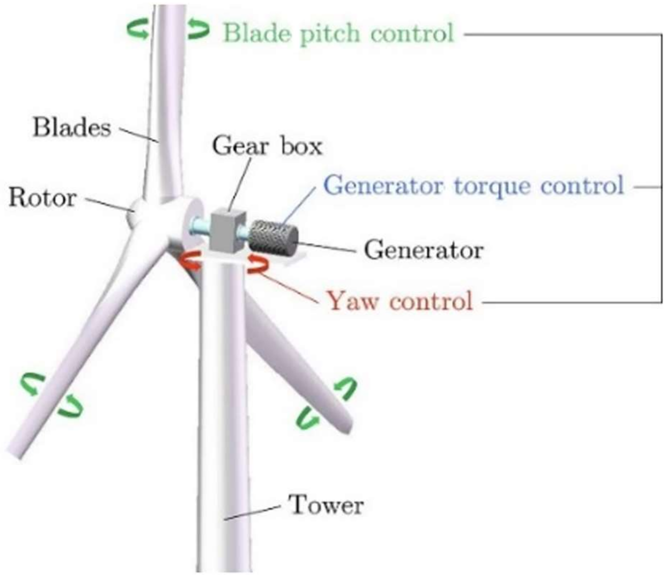

Figure 3. Mechanical–electrical wind energy conversion system. Reproduced with permission from [78], Elsevier (Amsterdam, The Netherlands), 2022.

There are two energy conversion processes in the mechanical–electrical wind energy conversion scheme. First, wind energy is converted into mechanical energy, and the generator transforms that mechanical energy into electrical energy. However, the generator's output power is subject to instability due to the uncertainty and intermittency of wind. Consequently, additional energy storage and regulation components are necessary for wind turbine systems.

2.1.2. Mechanical–Hydraulic Schemes

Many researchers have integrated hydraulic transmission technology into offshore wind turbines to reduce system complexity and improve energy transmission efficiency. A typical mechanical–hydraulic wind energy conversion scheme is shown in Figure 4. These systems first convert wind energy into mechanical energy, and then convert that mechanical energy into hydraulic energy. Although mechanical–hydraulic wind energy conversion schemes have not been implemented in commercial hybrid wind–wave systems, they offer significant advantages such as stepless speed regulation, a high power-to-weight ratio, flexible transmission, and low maintenance costs [79,80]. In recent years, there has been a clear upward trend in the number of the studies focusing on these systems [81,82].

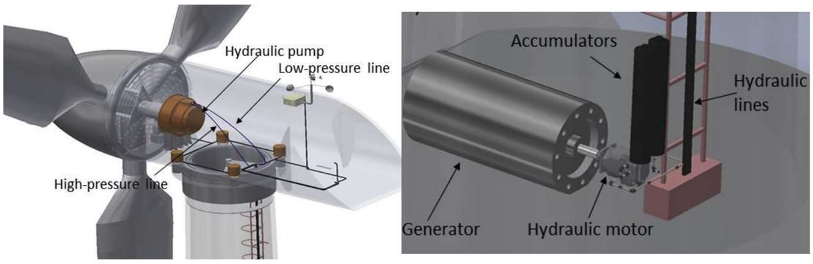

Figure 4. Mechanical–hydraulic wind energy conversion system. Reproduced with permission from [81], Elsevier (Amsterdam, The Netherlands), 2020.

2.2. Wave Energy Conversion Technologies

Various wave energy converters have emerged worldwide over the past few decades and their performance has been systematically studied [83–87]. A comprehensive wave-to-wire model was developed to evaluate wave energy's conversion from sea resources to the grid [88]. In hybrid wind–wave systems, wave energy converters are installed on the foundation of offshore wind turbines. Based on their working principles, the wave energy conversion technologies of hybrid wind–wave systems can be classified into three types: oscillating bodies, oscillating water columns, and overtopping.

2.2.1. Oscillating Bodies Systems

Oscillating bodies systems (OBs) are widely employed in existing hybrid wind–wave systems, as shown in Figure 5. Notable examples include Wave Star [58,89], Pelamis [90], and W2Power [72]. Many conceptual prototypes have been developed in recent years [91]. In hybrid wind–wave systems, OBs are installed on a floating or bottom-fixed platform to capture wave energy via the movements of various oscillating bodies [92]. The structures of OBs can be divided into oscillating bodies, Power Take-Off (PTO) systems, and generators. Oscillating bodies are excited by waves, which convert the wave energy into mechanical energy. The PTO system transmits the mechanical energy of the oscillating bodies to the generator.

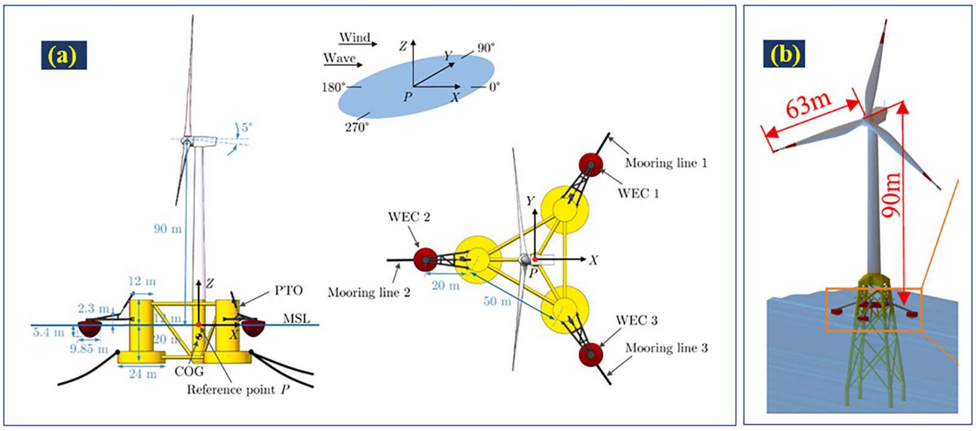

Figure 5. Hybrid wind–wave systems with OBs: (**a**) OBs installed on a floating platform. Reproduced with permission from [93], Elsevier (Amsterdam, The Netherlands), 2021. (**b**) OBs installed on a bottom-fixed platform. Reproduced with permission from [94], Elsevier (Amsterdam, The Netherlands), 2024.

There are two types of PTO systems in OBs: hydraulic and direct-drive PTO systems. The hydraulic PTO scheme is widely applied because of its high energy transmission efficiency, simple structure, and strong controllability [95]. A typical hydraulic wave energy PTO system, illustrated in Figure 6, consists of a hydraulic cylinder, hydraulic pipelines, hydraulic control and regulation components, and a hydraulic motor. A hydraulic cylinder can convert wave energy into hydraulic energy [96]. Hydraulic control and regulation components can reduce the pressure fluctuations across the entire system [97].

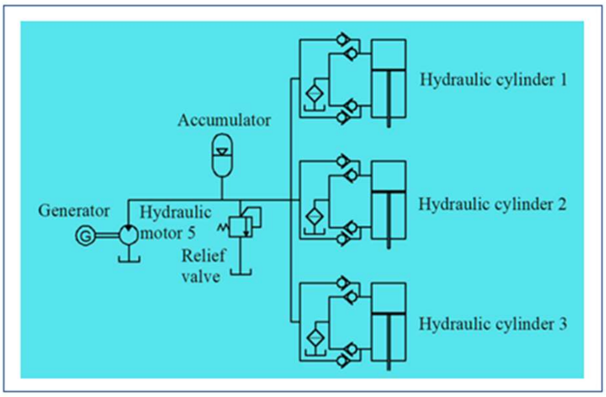

Figure 6. The hydraulic PTO system of the OBs in hybrid wind–wave systems. Reproduced with permission from [63], Elsevier (Amsterdam, The Netherlands), 2022.

In recent years, several conceptual prototypes have been developed for direct-drive PTO systems [98–101]. Direct-drive PTO systems can be classified as mechanical-drive and electrical-drive, as illustrated in Figure 7. A mechanical-drive PTO system comprises various mechanical components that transmit the mechanical energy of the oscillating bodies to the generator shaft. This complex structure increases the energy loss and decreases the system's life. In contrast, an electrical-drive PTO system consists of a linear generator and a simple mechanical structure. The oscillating body is excited by waves and drives the linear generator to generate electricity.

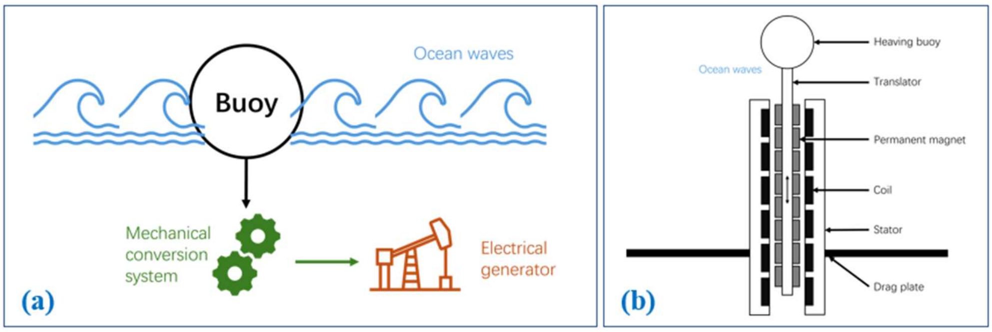

Figure 7. Direct-drive PTO systems in the OBs of hybrid wind–wave systems: (**a**) Direct mechanical-drive PTO system. (**b**) Direct electrical-drive PTO system.

2.2.2. Oscillating Water Column Systems

Although OBs have been used in several commercial projects, the high damage rate of their mechanical components results in high maintenance costs [102–104]. Compared with other wave energy converters, oscillating water column devices (OWCs) are more suitable for integration into hybrid wind–wave systems. OWCs consist of a semi-submerged chamber and a turbo generator (Figure 8). OWCs have the advantages of a simple structure and long operating life [105,106]. The waves continually move up and down, compressing the air out of the chambers and then back into them through the turbo generator. The turbo generator is driven by airflow.

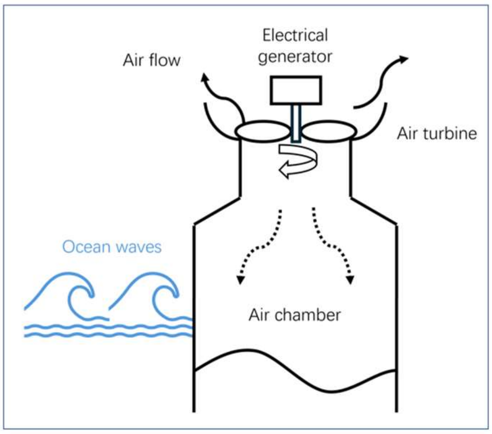

Figure 8. Schematic of the OWC device.

Based on this foundation, hybrid wind–wave systems utilising OWCs are primarily categorised into bottom-mounted and floating systems, as shown in Figure 9. In a bottom-mounted system, an offshore wind turbine is fixed to the seabed. The OWCs are installed onto the wind turbine tower. The floating-type system involves mounting both the offshore wind turbines and the OWCs on a shared floating platform [107].

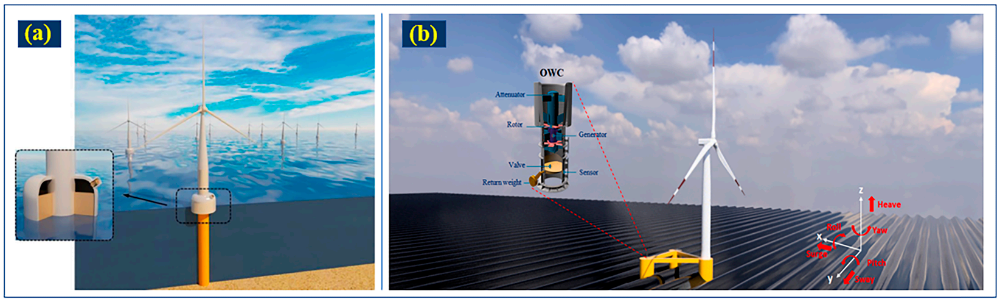

Figure 9. Conceptual drawings of hybrid wind–wave systems with OWCs: (**a**) Bottom-mounted type. Reproduced with permission from [108], Elsevier (Amsterdam, The Netherlands), 2021. (**b**) Floating type. Reproduced with permission from [109], Elsevier (Amsterdam, The Netherlands), 2024.

2.2.3. Overtopping System

Existing research on overtopping wave energy converters is scarcer than that on OBs and OWCs. The number of hybrid wind–wave systems that employ overtopping wave energy converters is limited. The primary advantage of overtopping wave energy converters is their structural simplicity. A schematic drawing of an overtopping wave energy converter is shown in Figure 10. Waves run up along a ramp and flow into a reservoir installed at a level higher than the sea. The water drives a hydro-turbine connected to a generator via water flow [110].

At present, there are only a few studies on hybrid wind–wave systems that employ overtopping wave energy converters. The most well-known demonstrations are WPR and 2Wave1Wind, developed by OWWE [112]. Fiaschi et al. proposed an offshore multi-energy exploitation system with a yearly energy production potential of 177,000 kWh [113]. The overtopping wave energy converter used in this system was a Wave Dragon (Figure 11a). Moschos et al. designed a hybrid wind–wave system containing two offshore wind turbines and four overtopping wave energy converters (Figure 11b). The output power of this system was 2000 kW [40]. However, hybrid wind–wave systems employing overtopping wave energy converters have disadvantages, such as high construction and maintenance costs, low mobility, and intermittent power generation, which limit their application.

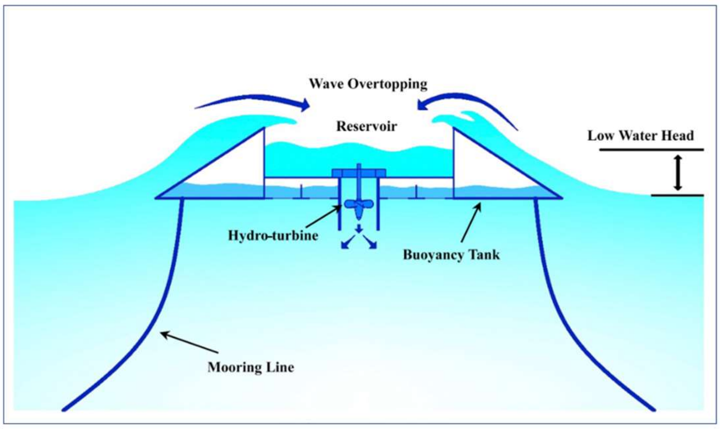

Figure 10. Schematic drawing of an overtopping wave energy converter. Reproduced with permission from [111], Elsevier (Amsterdam, The Netherlands), 2017.

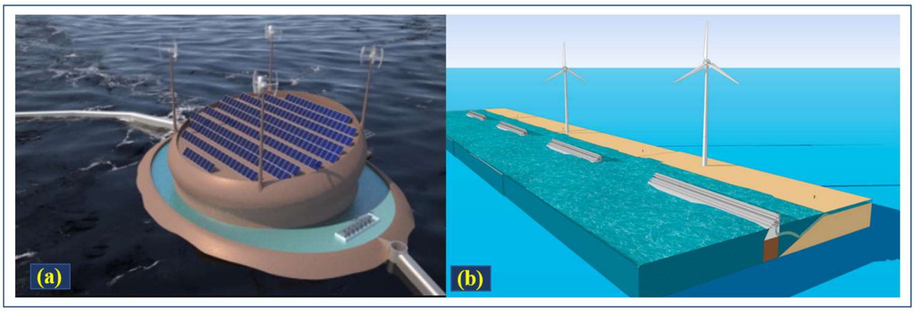

Figure 11. Schematic representation of hybrid wind–wave systems employing overtopping wave energy converters: (**a**) Versatile offshore platform. Reproduced with permission from [113], Elsevier (Amsterdam, The Netherlands), 2012. (**b**) Hybrid renewable energy system. Reproduced with permission from [40], Elsevier (Amsterdam, The Netherlands), 2017.

3. Energy Coupling Technologies

Currently, mainstream research on hybrid wind–wave systems focuses on their hydrodynamic performance and resource assessments. However, only a limited number of studies have been conducted on energy coupling technologies. This section summarises and analyses the energy coupling technologies of current hybrid wind–wave systems. The energy coupling subsystem used significantly influences the electric energy production of the entire system. According to their working principles, the energy coupling technologies used in existing hybrid wind–wave systems are classified as electrical or hydraulic coupling. These specific classifications are presented in Figure 12.

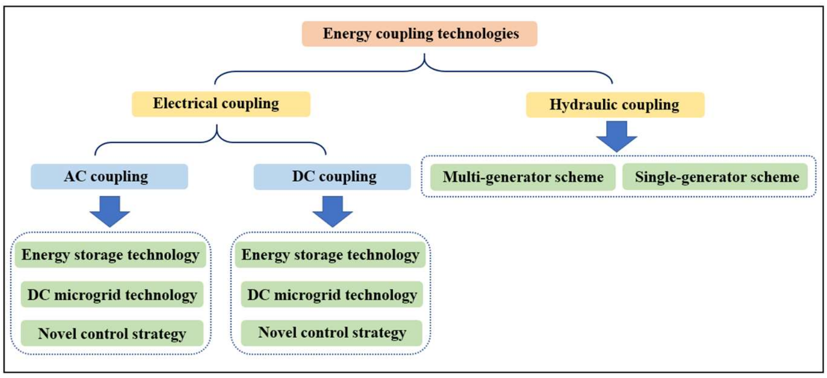

Figure 12. Classification of the energy coupling technologies of existing hybrid wind–wave systems.

3.1. Electrical Coupling

Electrical coupling schemes utilise electrical components to integrate and regulate the power from both wind and wave sources. Electrical coupling schemes are widely applied in currently active hybrid wind–wave systems, such as Poseidon37, W2Power, WaveStar, and WaveTreader. Based on their type of coupled voltage, electrical coupling schemes can be further classified into AC and DC coupling schemes.

3.1.1. AC Coupling

AC coupling schemes offer the advantages of a simple structure and low costs. The configuration of an AC coupling scheme is shown in Figure 13. In this setup, AC/DC converters (rectifiers) are employed to convert the alternating currents generated by different generators into direct currents. These direct currents are then transformed into alternating currents of the same frequency using DC/AC converters (inverters). Finally, the alternating currents from different circuits are connected to the grid.

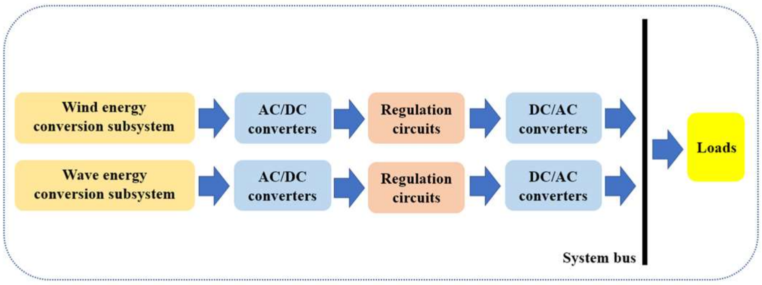

Figure 13. Configuration of AC coupling schemes.

The back-to-back pulse-width modulation (PWM) converter is the primary variable-frequency controller in existing AC coupling schemes due to its strong controllability, reliability, and flexibility. A typical back-to-back PWM circuit is shown in Figure 14. Currently, the research on AC coupling schemes can be classified into two categories: one focuses on the topological optimisations of back-to-back PWM conversion circuits, while the other focuses on various control strategies.

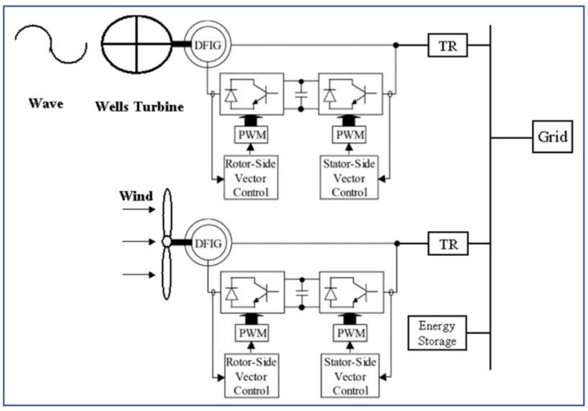

Figure 14. Schematic representation of back-to-back PWM converters integrated into a hybrid wind–wave system. Reproduced with permission from [75], Elsevier (Amsterdam, The Netherlands), 2019.

AC Microgrid Technology

Microgrid technologies provide an efficient approach for enhancing system performance. Wang et al. presented a microgrid system aimed at achieving the hybrid extraction of offshore wind energy and wave energy. This system comprises a voltage source converter, high-voltage DC link, and damping controller [114]. Soundarya et al. designed a hybrid DC/AC microgrid to integrate captured offshore renewable energy and introduced a maximum power point tracking fuzzy control algorithm [115].

Novel Control Strategies

Novel control strategies have been proposed recently. The authors in [75] proposed a hybrid wind–wave system that applied an optimised intelligent neural network controller to enhance the dynamic performance of their system and maximise energy harvesting. The entire system was simulated and analysed using PSCAD/EMTDC V4 software. Qin et al. proposed an offshore hybrid power generation system using a coordinated control method [116]. This system uses grid voltage regulators and DC-link voltage regulators to control the system's voltages. In [117], an innovative method was proposed to regulate the voltages and currents of a multiport magnetic bus, and a damping controller was designed to maximise wave energy harvesting.

3.1.2. DC Coupling

With the rapid development of power electronics, numerous innovative DC coupling systems have been integrated into hybrid wind–wave systems in recent years. The configuration of DC coupling schemes is shown in Figure 15. Initially, the alternating currents generated by the different generators are converted into direct currents by AC/DC converters. Subsequently, the direct currents are integrated. Finally, the coupled direct current is adjusted by the regulation components and converted back into an alternating current by the DC/AC converters.

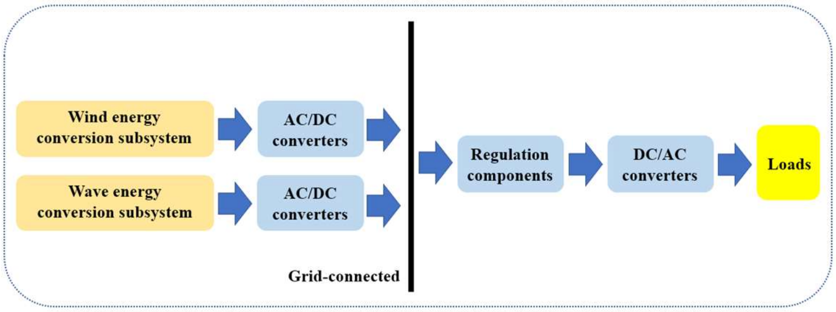

Figure 15. Configuration of DC coupling schemes.

DC Microgrid Technology

Compared with AC microgrids, DC microgrids are more flexible and reliable. Lu et al. proposed a hybrid wind–wave system with a DC microgrid that connected a wind turbine and a wave energy converter via AC/DC converters [64,118]. The entire system was modelled and simulated using MATLAB/Simulink, and its power performance under various operational conditions was analysed. Talaat et al. presented a multi-energy integrated system consisting of an AC/DC converter and a DC/DC converter [76]. The wind and wave energy conversion systems were integrated into a DC busbar, and a buck-boost circuit was designed to maintain a stable DC busbar voltage.

Novel Control Strategies

Additionally, several innovative approaches based on DC coupling circuits have been explored. Chen et al. combined a wind turbine with a direct-drive wave energy converter and designed a full-bridge controlled rectifier circuit to integrate wind and wave energies [66]. The authors of [100] proposed a hybrid wind–wave system capable of providing stable power to customers on remote islands. This system employed a doubly fed induction generator for wind energy capture and a linear permanent magnet generator for wave energy capture. Rasool et al. proposed a hybrid wind–wave system with a distribution network that employed back-to-back converters to maximise the energy extraction from wind and wave energy [101].

3.1.3. Energy Storage Technology

Energy storage technologies for electrical coupling systems can be divided into two types: batteries and mechanical storage. Battery storage systems typically use lithium-ion, lead-acid, or other types of batteries to chemically store electricity. When the electricity demand increases or decreases, the stored energy can be discharged from the batteries to supply power to the grid [119]. Mechanical storage elements store energy either mechanically or kinetically.

Zhang et al. proposed a hybrid wind–wave system with an integrated energy storage system [120]. In this system, the proposed integral compensation control method maximises energy capture and regulates the rotation speed of the wind turbine rotor. The alternating currents generated by the wind and wave energy conversion subsystems are integrated into the system bus after being regulated by back-to-back PWM converters and transformers. Liu et al. innovatively applied multitoothed doubly salient permanent magnet machines to serve different generators and used a battery tank to store excess energy [121]. Li et al. proposed a hybrid wind–wave system connected to a large power grid through a flywheel energy storage system [122]. They found that this flywheel energy storage system effectively stabilised power fluctuations. In another study [123], researchers proposed a novel hybrid wind–wave system comprising an offshore wind turbine and a point absorber with a hydraulic PTO system. The power sharing among different generators was governed based on their DC-link voltage, and two mechanical storage schemes were employed to smooth the DC voltage fluctuations at the DC coupling point.

Battery storage systems offer fast response times and can be easily scaled to meet various energy storage requirements. However, they have a limited energy capacity and lifespan, and there are concerns regarding the environmental impact of battery production and disposal [124]. Mechanical storage elements can provide larger energy storage capacities and longer lifespans but may have slower response times and higher upfront costs [122].

3.2. Hydraulic Coupling

In hydraulic coupling schemes, the energy from the wind and wave energy conversion subsystems is integrated and regulated using hydraulic components. The configuration of a hydraulic coupling scheme is shown in Figure 16. Although no commercial projects have employed hydraulic coupling schemes, existing studies have demonstrated their excellent power performance. Compared to electrical coupling, hydraulic coupling can reduce maintenance costs and enhance the system's operating life due to its simplified structure. Based on the number of generators, hydraulic coupling schemes are further classified into multi-generator schemes and single-generator schemes.

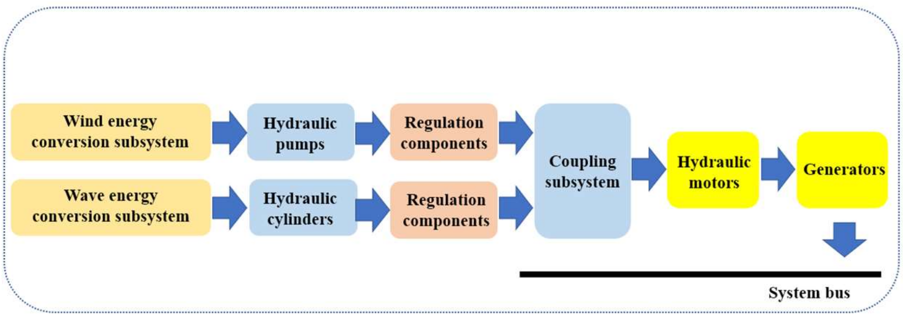

Figure 16. Configuration of hydraulic coupling schemes.

3.2.1. Multi-Generator Schemes

A typical multi-generator scheme is shown in Figure 17. However, research on multi-generator schemes is limited. One notable engineering case is the W2P proposed by Chen et al., which comprises an offshore wind turbine and three oscillating body wave energy converters. This system demonstrated a wave energy conversion efficiency of over

80% [125]. In this system, the energy conversion subsystems convert wind and wave energies into hydraulic energy. Hydraulic oil from different hydraulic circuits is regulated and integrated by accumulators. Finally, the hydraulic motors connected to the generators are driven.

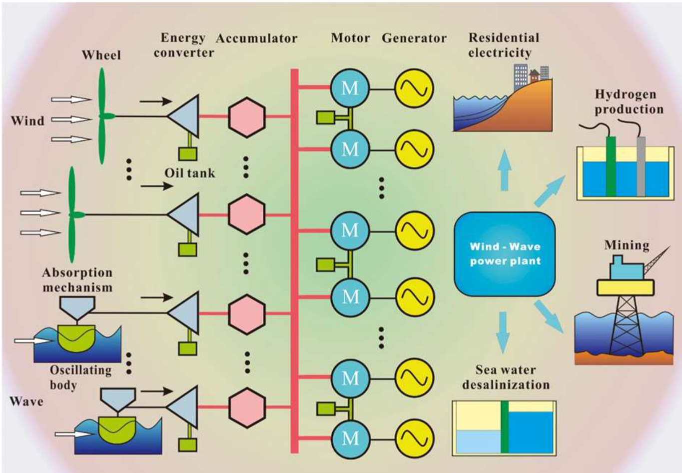

Figure 17. Schematic representation of W2P. Reproduced with permission from [125], Elsevier (Amsterdam, The Netherlands), 2019.

3.2.2. Single-Generator Schemes

A typical single-generator scheme is illustrated in Figure 18. There is only one generator in this energy coupling system. Compared with multi-generator schemes, single-generator schemes further simplify their system structure, resulting in a higher price performance ratio and longer operating life.

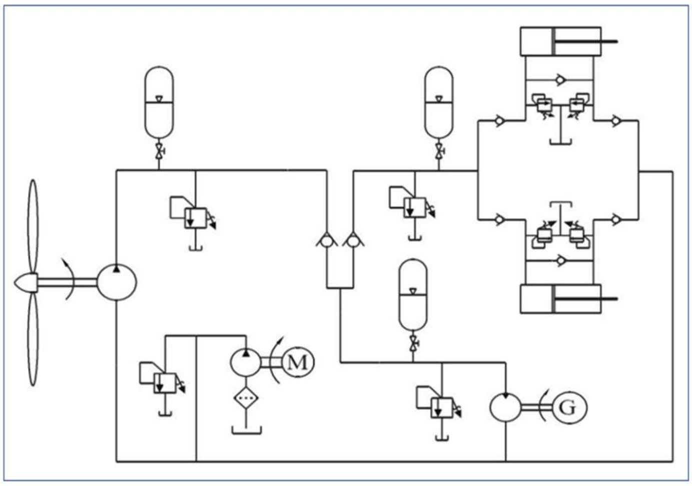

Figure 18. Schematic representation of the hybrid wind–wave system in a single-generator scheme.

Shi et al. designed a hybrid wind–wave system with hydraulic transmission that consisted of an offshore wind turbine and two oscillating body wave energy converters [126]. The system was simulated using MATLAB/Simulink 2016 and AMESim 17.0 software. The results showed that the energy coupling efficiency of the system was maintained at 75%. Tri et al. proposed a hybrid wind–wave system containing a vertical-axis wind turbine and two wave buoys [127]. This system utilised a variable-inertia hydraulic flywheel to maximise its energy extraction from waves. However, this system lacks an effective control strategy; therefore, its overall efficiency is only 41.5%.

Zhejiang University (ZJU) proposed an on–off controlled hybrid wind–wave system that employs electromagnetic directional valves and pressure sensors to realise the energy coupling of different hydraulic circuits [128]. This scheme effectively reduces the negative coupling effect between two energy conversion subsystems. To minimise the energy losses resulting from interrupted flow rates, ZJU proposed a pressure-regulating hybrid wind–wave system utilising two additional hydraulic pumps to match the pressure levels [129]. Kong et al. proposed a hybrid wind–wave system with hydraulic transmission, which utilised an accumulator and a variable displacement pump for short-term energy storage [130]. Wang et al. proposed a novel hybrid wind–wave system with an adaptive motor speed control method [63]. The system was simulated using MATLAB/Simulink and AMESim 19.0 software. The simulation results indicated an average energy coupling efficiency of 89%.

4. Discussion

Representative hybrid wind–wave systems worldwide, established from 2010 to 2023, are listed in Table 1. Because studies on hybrid wind–wave systems are still at an early stage, discussions about their energy conversion and coupling technologies are crucial.

Table 1. Representative hybrid wind–wave systems worldwide from 2010 to 2023.

Year	Inventor	Wind Conversion Scheme	Wave Conversion Scheme /PTO System	Energy Coupling Scheme	Capacity
2010	Pelagic Power AS [72]	Mechanical–electrical	OBs/hydraulic PTO	Electrical coupling	10 MW
2010	Green Ocean Energy [71]	Mechanical–electrical	OBs/hydraulic PTO	Electrical coupling	600 kW
2011	Principle Power Inc [74]	Mechanical–electrical	OBs/hydraulic PTO	Electrical coupling	7 MW
2012	Wave Star AS [89]	Mechanical–electrical	OBs/hydraulic PTO	Electrical coupling	600 kW
2012	Fiaschi et al. [113]	Mechanical–electrical	Overtopping/electrical PTO	Electrical coupling	50 kW
2013	Shi et al. [126]	Mechanical–hydraulic	OBs/hydraulic PTO	Hydraulic coupling	15 MW
2014	Liu et al. [131]	Mechanical–electrical	OBs/direct-drive PTO	Electrical coupling	500 W
2015	Kim et al. [132]	Mechanical–electrical	OWCs/electrical PTO	Electrical coupling	10 MW
2016	Chen et al. [125]	Mechanical–electrical	OBs/hydraulic PTO	Hydraulic coupling	100 MW
2017	Moschos et al. [40]	Mechanical–electrical	Overtopping/electrical PTO	Electrical coupling	500 kW
2017	Chen et al. [66]	Mechanical–electrical	OBs/direct-drive PTO	Electrical coupling	5 kW
2018	Floating Power Plant [133]	Mechanical–electrical	OWCs/electrical PTO	Electrical coupling	7 MW
2019	Sarmiento et al. [134]	Mechanical–electrical	OWCs/electrical PTO	Electrical coupling	8 MW
2020	Zhu et al. [135]	Mechanical–electrical	OWCs/electrical PTO	Electrical coupling	10 kW
2021	Si et al. [93]	Mechanical–electrical	OBs/hydraulic PTO	Electrical coupling	4.7 MW
2021	Aboutalebi et al. [136]	Mechanical–electrical	OWCs/electrical PTO	Electrical coupling	7 MW
2022	Wang et al. [63]	Mechanical–hydraulic	OBs/hydraulic PTO	Hydraulic coupling	20 KW
2023	Zhang et al. [137]	Mechanical–hydraulic	OBs/hydraulic PTO	Hydraulic coupling	50 KW

4.1. Wind Energy Conversion Technologies

Currently, mechanical–electrical wind energy conversion schemes account for a large proportion of wind energy conversion technologies. They have been applied in many demonstration projects, whereas mechanical–hydraulic wind energy conversion schemes are still in the conceptual stage or are under study in model experiments. The primary reason for this is that the relevant technologies for mechanical–electrical schemes are more mature than those for mechanical–hydraulic schemes. A detailed comparison between mechanical–electrical and mechanical–hydraulic schemes is presented in Table 2. The Levelized Cost of Energy (LCOE) is a standardized way to compare the economic competitiveness of different energy technologies [138]. After a comprehensive assessment, the LCOE of mechanical–hydraulic schemes was found to be higher than that of mechanical–electrical schemes. Although mechanical–hydraulic schemes have not yet reached full maturity, their significant advantages have been identified. Moreover, the number of studies on hydraulic wind turbines has rapidly increased in recent years. Therefore, mechanical–hydraulic wind energy conversion schemes have great potential to provide a cost-effective method to accelerate the development of hybrid wind–wave systems.

Table 2. Comparison between two wind energy conversion schemes.

Evaluation Indexes	Mechanical–Electrical	Mechanical–Hydraulic
System volume	Large	Compact
Numbers of components	Many	Few
Energy conversion times	3 times	3 times
Control difficulty	Complex	Simple [79]
Reliability	Lower [139]	Higher
Transmission efficiency	lower	Higher [140]
Economic costs	Higher [141]	Lower
Technological maturity	Mature	Immature

4.2. Wave Energy Conversion Technologies

A detailed comparison of the different wave energy conversion schemes is presented in Table 3. Overtopping systems are suitable for integration into existing structures but require a large reservoir volume. OWCs offer simplicity and versatility but are sensitive to wave conditions. OBs have the potential for higher efficiency but may be more complex. Compared with overtopping systems and OBs, OWCs have the most balanced LCOE in terms of cost and efficiency [142]. The use percentages of the different wave energy conversion schemes from 2012 to 2023 are shown in Figure 19a. OBs and OWCs are the most widely used in existing hybrid wind–wave systems, whereas overtopping schemes are scarce because of their high installation and maintenance costs. OBs are widely used due to their high efficiency. However, complex mechanical and hydraulic systems have increased initial capital and maintenance costs and reduced operational lifespans.

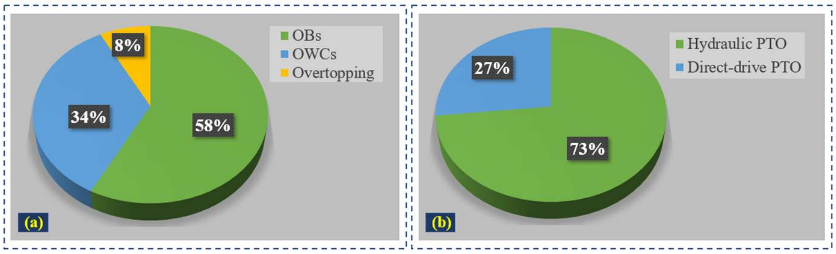

Figure 19. Percentages of the different wave energy conversion schemes and different PTO systems of OBs from 2012 to 2023: (**a**) percentages of different wave energy conversion schemes used; (**b**) percentages of the different PTO systems of OBs.

The number of studies on the hybrid wind–wave systems using OWCs has gradually increased in recent years. Among the various wave energy converters, the energy capture efficiencies of OWCs are relatively high [104,143]. OWCs can be installed on wind turbine towers, platform foundations, or floating platforms, exhibiting strong construction flexibility. In addition, OWCs exhibit a long operating life and strong adaptability to various operating conditions [144]. The combination of OWCs with offshore wind turbines for hybrid energy exploitation has attracted increasing attention worldwide.

The distribution of different Power Take-Off (PTO) systems applied to the OBs in existing hybrid wind–wave systems from 2012 to 2023 is depicted in Figure 19b. Hydraulic PTO systems are widely used due to their extended operating life and effective control of power fluctuations [149]. In contrast, direct-drive PTO systems require numerous electrical components in the backend power grid to control their power fluctuations during energy transmission, which increases their energy losses [150].

Table 3. Comparison between different wave energy conversion schemes.

Scheme	Advantages	Disadvantages
OBs	1. Can capture energy from a wide range of wave directions [86] 2. Higher efficiency compared to some other wave energy conversion systems [145]	1. Complex mechanical and hydraulic systems 2. High initial capital and maintenance costs [146]
OWCs	1. Simple design 2. Lower maintenance costs 3. Can be integrated into various coastal structures [104]	1. Efficiency can be affected by variations in wave height and period 2. Limited to specific locations with suitable wave conditions [142]
Overtopping	1. Can be integrated into existing harbour structures or artificial breakwaters [147] 2. Suitable for a wide range of wave conditions	1. Requires a substantial reservoir volume 2. Efficiency can be affected by variations in wave height and period [148]

4.3. Energy Coupling Technologies

Electrical coupling schemes account for a large proportion of energy coupling technologies due to their maturity. A detailed comparison of AC and DC coupling is presented in Table 4. AC coupling schemes have the advantages of simple structures and low construction costs. However, they are inevitably affected by cable capacitance, which leads to high energy losses and severe harmonic interactions [151]. With an increase in the cable length, the energy losses increase rapidly. Therefore, AC coupling may be a cost-effective choice for small-capacity hybrid wind–wave systems with short-distance transmission cables. In contrast, DC coupling schemes can effectively regulate active and reactive power, presenting advantages such as a stronger fault ride-through capability, fewer control parameters, and increased reliability and flexibility. Consequently, DC coupling has a lower LCOE than AC coupling and has garnered increasing attention.

Table 4. Comparison between AC coupling and DC coupling.

Evaluation Indexes	AC Coupling	DC Coupling
System structure	Simple	Complex
Control difficulty	Simple	Difficult
Reliability	Lower [152]	Higher [153]
Innovation space	Large	Large
Expandability	Finite	Strong [154]
Fault ride-though capability	Low	Strong [155]

The number of relevant studies on hydraulic coupling schemes is fewer than those on electrical coupling schemes. However, existing hydraulic coupling schemes exhibit an excellent overall performance, including high energy coupling efficiency, low maintenance costs, and a long operating life. Hydraulic coupling schemes also exhibit strong adaptability under different operating conditions, which increases the economy of the system [156]. A detailed comparison between hydraulic coupling and electrical coupling is presented in Table 5. Compared to electrical coupling schemes, hydraulic coupling schemes have a longer operating life due to their simpler structures. Moreover, hydraulic transmission systems exhibit lower energy losses than electrical transmission systems [63].

Table 5. Comparison between hydraulic coupling and electrical coupling.

Evaluation Indexes	Electrical Coupling	Hydraulic Coupling
System structure	Complex	Simple
Storage element	Mechanical storage of battery	Accumulator
Adaptability	Lower	Stronger [157]
Transmission efficiency	Lower [158]	Higher [123]
Innovation space	Large	Large

Furthermore, the selection of energy coupling schemes must consider backend energy transmission systems. High-voltage direct current (HVDC) and high-voltage alternating current (HVAC) are the primary energy transmission modes in ocean energy generation systems [159]. An HVDC is more suitable for systems requiring long-distance transmission with high controllability and stability [160]. Conversely, an HVAC is preferable for systems with shorter distances and lower costs. DC coupling schemes can directly employ HVDC technology to transmit electrical energy to power stations. AC and hydraulic coupling schemes can utilise an HVAC for transmitting electrical energy to a power station, although it is only suitable for short-distance power transmission. AC coupling schemes can rectify alternating currents into direct currents before employing HVDC for power transmission; however, their energy losses increase [161]. Due to their high energy coupling efficiency, hydraulic coupling schemes can rectify alternating current into direct current and utilise HVDC for power transmission. With the rapid development of offshore renewable energy generation systems in deep water, both DC coupling and hydraulic coupling are expected to become the mainstream schemes in the future.

4.4. Seasonal Influences

Wind patterns can vary seasonally, at certain times of the year. In regions with pronounced wind seasonality, the energy output of the wind turbines within hybrid systems may fluctuate accordingly. This can affect the overall energy production and reliability of the system, requiring adjustments in energy management and grid integration strategies [31]. Similar to wind, wave patterns can also exhibit seasonal variability, with changes in wave height, period, and direction throughout the year [162]. Seasonal variations in wave energy can influence the performance of the wave energy converters within hybrid systems, impacting their energy capture efficiency and overall output. Design changes should be made to optimize the system's performance under different wave conditions. In addition, exposure to harsh weather conditions during certain seasons increases the risk of the corrosion, erosion, or mechanical wear of system components [163], necessitating enhanced maintenance and monitoring protocols.

4.5. Technological Gaps

To accelerate the development of hybrid wind–wave systems, some challenges in energy conversion and coupling subsystems must be overcome:

- Short operating lives. Most hybrid wind–wave systems employ OBs. Damage to their mechanical components significantly decreases their operating life.
- Low energy production. The development of energy conversion and coupling technologies for hybrid wind–wave systems is still in its early stages. Energy production has not yet reached its maximum level.
- Limited economic viability. High maintenance costs reduce the economy of these systems.
- Scarcity of theoretical research and experimental tests. At present, there are a limited number of studies on the energy conversion and coupling technologies of hybrid wind–wave systems. The existing numerical models and experimental studies are not sufficient to support their further development.

4.6. Technology Development Forecasts

In this section, development forecasts for the energy conversion and coupling technologies of hybrid wind–wave systems are presented.

In terms of energy conversion technologies, integrating oscillating water column devices and hydraulic wind turbines into hybrid wind–wave systems has the potential to enhance their operating life, energy production, and system economy [45]. This will be a future research trend. Existing studies on energy coupling technologies are scarce. Therefore, theoretical innovations and novel technical schemes are required. DC coupling and hydraulic coupling will be the mainstream schemes in the future, considering their reliability, energy transmission efficiency, construction costs, and applicability in deep-sea environments [63,109].

5. Conclusions

This study provides a complete review of the energy conversion and coupling technologies of existing hybrid wind–wave systems that have not been comprehensively reviewed before. Our original contributions include a detailed classification and comparison of energy conversion and coupling technologies, the identification of existing technological gaps, and forecasts on the development of these technologies. Based on the obtained information, the following conclusions were drawn:

(1) Mechanical–electrical wind energy conversion schemes account for a large proportion of existing hybrid wind–wave systems. However, mechanical–hydraulic schemes have more prominent advantages, including compact sizes, simple control methods, high reliability, high energy transmission efficiency, and low economic costs.
(2) The use percentages of different wave energy conversion schemes from 2012 to 2023 were presented. The percentages schemes implementing OBs, OWCs, and overtopping systems were 58%, 34%, and 8%, respectively.
(3) Of the different wave energy conversion technologies, OWCs have the most balanced LCOE. Integrating oscillating water column devices and hydraulic wind turbines into hybrid wind–wave systems is the most promising choice.
(4) The distribution of the different PTO systems applied to the OBs in existing hybrid wind–wave systems from 2012 to 2023 was presented. Hydraulic PTO systems account for 73% of OBs, whereas direct-drive PTO systems account for 27%.
(5) DC and hydraulic coupling are expected to become mainstream schemes in the future. There remains a large innovative space for energy coupling technologies.
(6) Seasonal factors are crucial for the sustainable development of hybrid wind–wave power generation systems.
(7) Existing challenges in energy conversion and coupling technologies include their short operating life, low energy production, limited economic viability, and the scarcity of theoretical research and experimental tests.

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