Review

State of the Art in Wave Energy Conversion Technologies in China

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ABSTRACT: This paper reviews the advancements in wave energy converter technologies in China, covering device design, performance evaluation, and system control techniques. It highlights power control technologies in wave energy conversion, including adaptive control, model predictive control, clutch control, clamp control, resistive load control, approximate optimal speed control, nonlinear control, and intelligent control methods. Through an analysis of these technologies, the study outlines the future directions and challenges in wave energy development in China, while also proposing potential pathways for optimizing the performance of wave energy conversion devices.

Keywords: Wave energy; Wave energy conversion system; Power control; Development tendency

1. Introduction

The global community has increasingly turned its attention to ocean energy as a clean and renewable source, driven by the rising demand for energy and the diminishing availability of conventional fossil fuels [1–3]. Ocean energy, encompassing temperature differential energy, wave energy, tidal energy, and other forms, is considered a pivotal avenue for reshaping the future energy landscape due to its numerous advantages, including vast reserves, widespread distribution, and exceptional renewability [4–6]. In recent years, nations have made remarkable progress in the development and deployment of ocean energy technologies. Key research areas include the integration and intelligent evolution of ocean energy power generation systems, as well as the synergistic utilization of ocean energy alongside other energy sources [7,8].

Among various forms of ocean energy, wave energy has attracted significant research interest due to its high energy density and predictability. China, in particular, possesses abundant wave energy resources, with offshore and coastal wave energy reserves estimated at approximately 5.74×10^{11} kW, offering significant potential for large-scale generation [9–12]. Despite this vast potential, the practical implementation of wave energy conversion technologies still faces numerous challenges, including high costs, low efficiency, and structural durability issues in harsh marine environments. Although various wave energy converters (WECs) have been developed and tested, many still struggle to achieve economic viability and long-term reliability [13]. Moreover, the integration of wave energy with existing power grids and other renewable energy sources remains a complex issue that requires further investigation.

To address these challenges, significant research efforts have been dedicated to optimizing the design of wave energy conversion devices, improving power control strategies, and exploring novel materials and structural configurations. Recent advancements have shown promising progress in increasing energy capture efficiency, enhancing device survivability, and reducing overall costs. However, there remains a pressing need for further research in areas such as the development of robust and adaptive control systems, innovative mooring techniques, and scalable deployment strategies for wave energy arrays [14,15].

China has made notable progress in wave energy development, particularly in the research, development, and testing of wave energy conversion devices. Several wave energy converters have entered testing phases and exhibit promising potential for commercialization However, a comprehensive review of recent research efforts, technological

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advancements, and remaining challenges is essential to guide future development. Therefore, this review aims to systematically examine the latest progress and breakthroughs in wave energy technology, analyze the key challenges hindering its widespread application, and identify future research directions necessary to accelerate its large-scale implementation.

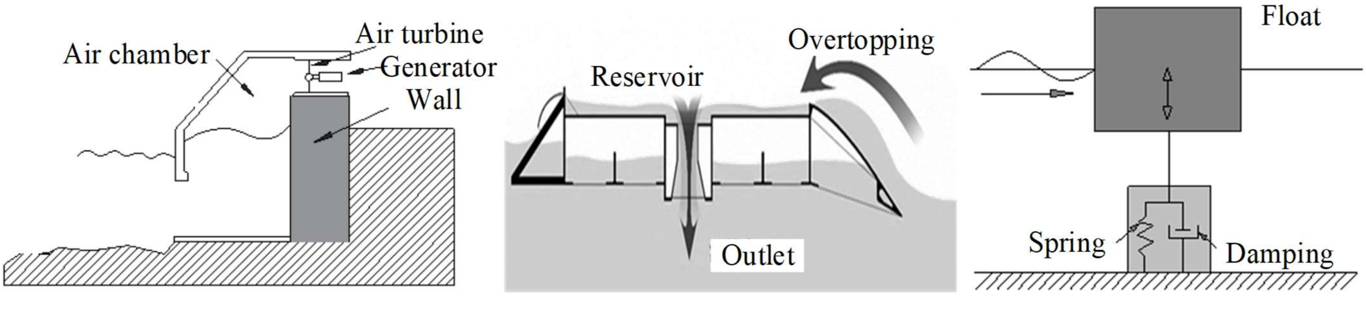
The remainder of this paper is organized as follows: Section 2 presents a classification of wave energy converters, including oscillating water columns, overtopping systems, and wave-activated body devices. Section 3 reviews recent developments in wave energy conversion technologies in China, categorized by the same classification. Section 4 discusses the development trends of wave energy generation devices in China, covering aspects such as multi-degree-of-freedom systems, WEC arraying strategies, multi-energy complementary coupling, multifunctional integrated platforms, and intelligent technology. Finally, Section 5 concludes the paper by summarizing key findings and providing insights into future research directions.

2. Classification of Wave Energy Converters

The wave energy generator operates on the following principle: the energy in the waves is captured by the energy-catching mechanism, then transferred, stored, and converted by the energy conversion and transfer system, ultimately being output as electrical energy. The conversion process typically unfolds in three stages: the first utilizes objects that respond to wave movements such as sinking, rocking, and other motions to convert these into mechanical or potential energy; the second stage employs an energy conversion and transfer system to transform the captured wave energy into generator energy; and the third stage involves the use of a generator and power conversion equipment, which constitute the primary means of tertiary conversion, producing the electrical power required by users. Consequently, the hydrodynamic subsystem, energy intake subsystem, reaction subsystem, and control subsystem are the key components of the wave energy device. Based on the working principle of the hydrodynamic subsystem, most wave energy devices can be classified into three main types: oscillating water columns, overtopping systems, and wave-activated bodies [16]. Additionally, these devices are further categorized by their location: stationary devices (typically deployed in near-shore shallow waters) and floating devices (designed for offshore deep-water environments).

2.1. Oscillating Water Column

The oscillating water column (OWC) device comprises an air chamber, the upper portion of which is connected to the atmosphere, often through an air pipe linked to an air turbine, while the lower portion is in communication with seawater via an opening, as shown in Figure 1a. The water column within the air chamber oscillates, inducing reciprocating airflow that drives the turbine, causing it to spin rapidly and generate electricity. This system offers advantages such as simple construction, energy conversion located above the water's surface, resistance to seawater corrosion, and ease of maintenance. However, the secondary energy conversion efficiency is relatively low, leading to higher power generation costs. Current research focuses on optimizing the air turbine and air chamber design, as well as investigating the coupling of the energy conversion process [17].



(**a**) (**b**) (**c**)

Figure 1. Schematic diagrams of (**a**) oscillating water column (OWC) device, (**b**) overtopping System and (**c**) wave-activated body device.

2.2. Overtopping System

In an overtopping system, as illustrated in Figure 1b, waves strike the coastal terrain or wave gathering structure, climbing over it to fill a high-level reservoir (or bank), thus creating a difference in water levels between the internal and external sides. This represents the first stage of energy conversion, wherein wave energy is transformed into the potential energy of the water body. When the reservoir reaches a sufficient water level for power generation, the stored water is released through a reflux pipeline, driving a low-head turbine within the pipeline. This constitutes the second stage of energy conversion, where the water's potential energy is converted into mechanical energy. The third stage is completed when the low-head turbine drives a generator, converting mechanical work into electrical power. Recent advancements have focused on developing new hydraulic systems and transmission mechanisms to enhance the stability and efficiency of the energy conversion process [18].

2.3. Wave-Activated Body

Wave-activated body devices utilize the oscillating motion of a body structure driven by wave action to create reciprocating motion, which is then converted into mechanical energy for object movement, thus completing the first stage of energy conversion. For the second stage, the oscillating body is integrated with an energy conversion-transfer mechanism, often a direct-drive mechanical or hydraulic system. The oscillating motion is subsequently converted into mechanical or hydraulic energy, completing the second stage of energy conversion. The third stage is achieved when a linear or hydraulic motor, connected to a generator, converts the mechanical or hydraulic energy into electrical power. Current research focuses on improving the efficiency of energy conversion through optimization of the oscillating body's design, particularly in terms of maximizing the motion amplitude and minimizing mechanical losses [16].

3. Recent Developments in Wave Energy Conversion Devices in China

3.1. Oscillating Water Column

Since the 1980s, oscillating water column wave power generation technology has been used in navigational lights. The BD102G device achieved an average observed power of 7.547 W (with a rated power of 10 W), significantly improving power generation efficiency while lowering manufacturing costs [12,19,20]. Subsequently, researchers began focusing on the development of Backward Bent Duct Buoy (BBDB) wave energy conversion technology. The world's largest 5 kW BBDB wave power float adopted a front-facing, rear-rounded floating chamber design and an extended rear section [21]. This float design not only delivered high peak power but also featured a smoother characteristic and a wider range of response wave periods. In 1996, the oscillating water column wave power plant on Dawanshan Island was upgraded to a 20 kW capacity plant after successful offshore operation tests [19]. The plant began trial power generation, reaching a peak output of 14.5 kW, with an energy capture efficiency ranging from 10 to 40 percent of the total energy. Subsequently, the Guangzhou Institute of Energy Conversion, Chinese Academy of Science, in Shanwei, Guangdong Province, established China's first grid-connected wave power plant using shore-based oscillating water column technology. The plant has an installed capacity of 100 kW [22].

However, due to the high costs associated with the construction and operation of large-scale oscillating water column wave energy generators, researchers have increasingly shifted their focus towards optimizing air turbines, the pressure characteristics of the air chamber within the conversion system, and wave breakwaters that utilize oscillating water columns [21,23]. Cui et al. [24] proposed a hybrid oscillating water column-oscillating buoy (OWCOB) wave energy converter, where the oscillating buoy is hinged to the OWC's outer wall. Using an analytical model based on linear potential flow theory, the study evaluated the OWCOB's energy capture performance and found that it outperforms stand-alone OWC and OB systems, particularly in terms of broader frequency bandwidth for wave power capture. Liu et al. [25] analyzed a stationary offshore platform with three oscillating water column (OWC) wave energy converters, finding that the seaward OWC achieves up to 97.4% efficiency under optimal conditions, and the energy capture of all three OWCs improves with increased device spacing. Wang et al. [26] examined a five-unit OWC array on a breakwater, revealing that while lateral units perform best, array interference and optimal transverse spacing are key factors in maximizing wave power capture. Cheng et al. [27,28] introduced a combined system of multiple OWCs and a long floating breakwater for sustainable wave energy extraction, analyzing energy conversion, gap resonance, and hydroelastic interactions. Simulations revealed that energy capture conflicts with wave attenuation, with optimal performance at specific OWC locations, while elastic deformation of the breakwater negatively affects energy conversion due to out-of-phase interference. Xu et al. [29] investigated the hydrodynamic performance of an OWC device integrated into an offshore wind turbine, analyzing key factors influencing energy capture and optimizing the device's performance under irregular wave conditions. Rao et al. [30] proposed a single floating OWC with two chambers separated by a buoyancy module (Figure 2), demonstrating high conversion efficiency in both small-scale and large-scale tests, with a peak CWR of 252.6% and wave-to-battery efficiency of 77.1%, offering a simple, cost-effective solution for open sea OWC operation.

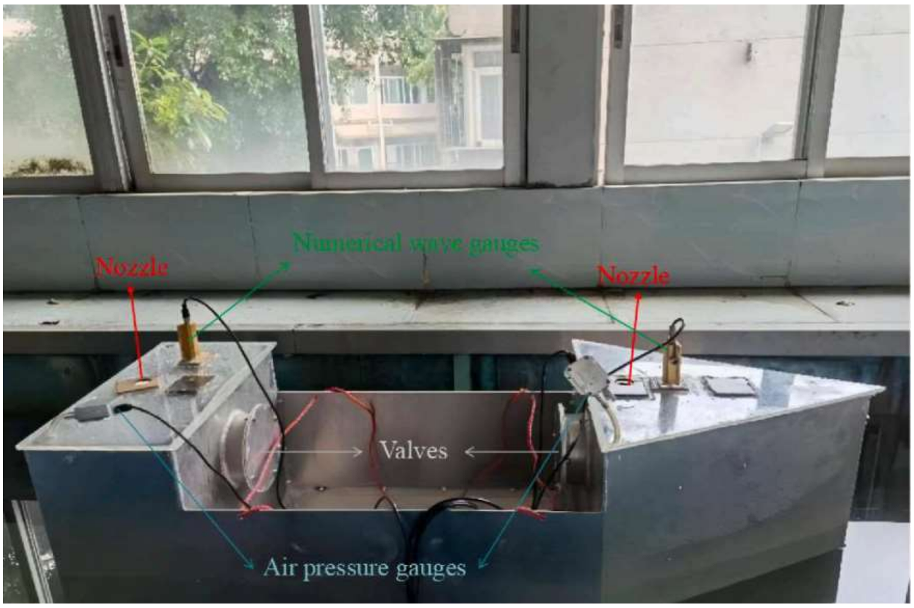


Figure 2. The concept of a single floating OWC with two chambers separated by a buoyancy module [30].

The team at Tsinghua University developed a high-efficiency, wide-bandwidth wave energy capture technology after nearly 20 years of devoted research [24,26,31–33]. They also constructed the most recent iteration of the "Hua Qing" device (Figure 3), which was successfully launched on 26 January 2025, in Jiangmen City, Guangdong Province. Its U-shaped flow channel air turbine combines outstanding dependability, wide frequency response, and efficiency. The system touts a 32% increase in capture breadth, a 70% improvement in frequency response range, and a 25% increase in air turbine efficiency when compared to current global technologies. Additionally, there is an 85% reduction in the load on the anchor chain. Through extensive experimental and numerical research, the team refined and optimized the design to address the enduring problems of high costs, poor cost-effectiveness, low dependability, and limited survivability of wave energy systems. Wang et al. [34] presented an integrated system of an offshore heaving OWC device and a floating breakwater, showing that optimizing the gap distance between them can maximize power extraction efficiency across various wave conditions. Also, Wang et al. [35] investigated the performance of a heaving OWC device restrained by a spring-damper system, showing that the proper spring value enhances power efficiency and expands frequency bandwidth, while the damper system helps reduce horizontal loads and improves structural safety, making it more adaptable to diverse wave conditions. Then, Guo et al. [36] developed and validated a fully coupled model for a BBDB-OWC wave energy converter, analyzing its transient characteristics, average performance, and the impact of wave conditions and load torque on efficiency. Further, Wang et al. [37] demonstrated the efficacy of a linear OWC array embedded in an inclined breakwater for enhancing wave energy extraction, showing that larger transverse spacing and a moderate slope profile improve performance, especially under long-period waves, with a 55.8% increase in power extraction compared to smaller spacing and vertical breakwater configurations. Xu et al. [38] used numerical methods to investigate the aerodynamic and hydrodynamic load characteristics of a floating pneumatic wave energy converter, analyzing the effects of wave parameters on the capture width ratio, chamber pressure, and pressure distribution on the converter structure under varying sea conditions.

Figure 3. The “Hua Qing” pneumatic wave energy conversion device.

Meanwhile, scientists have conducted extensive research on optimizing oscillating water column (OWC) wave energy converters, focusing on improving their hydrodynamic performance and energy conversion efficiency. Mahnamfar et al. [39] explored OWC optimization through numerical and experimental modeling, demonstrating that modifying the chamber’s geometry significantly enhances wave energy conversion efficiency. Their findings showed a strong correlation between numerical simulations and experimental results, with a Nash-Sutcliffe efficiency coefficient of 0.97, confirming the reliability of the model. Building on this, David et al. [40] investigated the influence of projecting sidewalls (harbor walls) on OWC efficiency, revealing that optimizing their length and inclination can enhance the conversion of wave energy into pneumatic power. Similarly, Parra-Quintero et al. [41] employed a numerical model to analyze the hydrodynamic performance of a U-shaped OWC chamber, achieving a peak efficiency of 66.8%. Their study further underscored the critical role of chamber geometry optimization in improving energy capture. In addition to structural modifications, researchers have also explored the interaction between OWCs and their power take-off (PTO) systems. Bouhrim and El Marjani [42] utilized a 2D RANS-VOF numerical model to investigate the coupling between an OWC chamber and an impulse turbine. Their study identified optimal turbine-induced damping as a key factor influencing OWC efficiency, emphasizing the importance of fine-tuning turbine parameters for maximum energy extraction.

OWC technology in China has seen significant advancements, transitioning from early applications in navigational lights to large-scale power plants and innovative hybrid systems. Early developments, such as the BD102G device and the Dawanshan Island power plant, demonstrated promising energy conversion efficiency and laid the foundation for further research. However, challenges such as high construction and maintenance costs have driven researchers to focus on optimizing key components, including air turbines, chamber pressure regulation, and integration with breakwaters. Recent studies have introduced various innovative configurations, including hybrid OWC-buoy systems, multi-OWC arrays, and OWC-integrated offshore wind turbines, aiming to enhance energy capture efficiency, broaden frequency response, and improve structural reliability. Notably, the “Hua Qing” device, developed by Tsinghua University, represents a breakthrough in OWC technology, boasting significant improvements in energy capture breadth, turbine efficiency, and system durability. Experimental and numerical research efforts continue to refine these technologies, addressing long-standing issues of cost-effectiveness, survivability, and adaptability to diverse wave conditions. As research progresses, OWC technology is expected to play a crucial role in China’s wave energy development, with ongoing innovations paving the way for more efficient and commercially viable wave energy conversion systems.

3.2. Overtopping System

The overtopping wave energy conversion system, constrained by factors such as installation location, coastline topography, and tidal variation, exhibits a significantly lower wave energy utilization rate compared to devices deployed in deeper waters. As a result, in comparison to oscillating body and oscillating water column devices, overtopping wave energy devices have seen relatively limited research and development investment, with most related systems remaining at the stage of physical model testing in laboratory conditions. In the early stages, Vicinanza et al. [43] reviewed the development and optimization of the Sea-wave Slot-cone Generator (SSG), an overtopping-based WEC designed for shoreline and breakwater integration, highlighting its efficiency, structural advantages, and ongoing pilot installations. Recently, Cavallaro et al. [44] developed a numerical model to optimize the performance of an innovative overtopping breakwater WEC, identifying key geometric parameters and control strategies to maximize energy output and support sustainable energy solutions for small Mediterranean islands. Ma et al. [45] established a 2-D hydrodynamic model for a layered slope-type overtopping wave energy device, validated it through Stokes wave theory and physical tests, and analyzed its overtopping wave characteristics, pressure distribution, and hydraulic efficiency under various conditions. Additionally, Liu et al. [46] analyzed the wave overtopping performance of a circular ramp wave energy converter using 3D numerical simulations and the VOF model for water-gas two-phase flow. By comparing numerical results with physical tests, the reliability of the established model was confirmed, and the optimal structural parameters of the device were determined, including the influence of slope number, blade count, and freeboard height. Moreover, the addition of a backflow plate is explored to reduce wave reflection, enhancing the optimal design of the converter.

Due to constraints such as installation site limitations and relatively low wave energy utilization, overtopping wave energy converters have received less research focus compared to other WEC types in China. Most developments remain at the laboratory testing stage, with efforts primarily centered on numerical modeling and physical validation. Recent studies have explored optimizing structural parameters and enhancing energy capture efficiency through slope design, blade configuration, and additional flow control mechanisms, laying the groundwork for future advancements in this technology.

3.3. Wave-Activated Body

The Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences, pioneered the development of China's first semi-submersible wave energy aquaculture net cage, named "Penghu", which was delivered for operation in 2019, as shown in Figure 4a. This innovative net cage provides a substantial volume of aquaculture water, accommodates up to 20 residents, and incorporates a solar power generation system, facilitating the integrated utilization of diverse energy sources [47,48]. In 2020, the wave energy generation system "Zhoushan" was officially commissioned, as shown in Figure 4b. This device employs a four-point anchoring system to secure it to the seabed and is equipped with a dual hydraulic PTO system, ensuring exceptional energy capture performance [49]. More recently, the "Nankun" (see Figure 5), as the world's first megawatt-scale wave energy converter, was developed by China Southern Power Grid in 2023 [50]. This innovative device, a trilateral semi-submersible platform, is equipped with five floating plates dedicated to energy conversion on each side. With a total surface area exceeding 3500 m^2 and a weight surpassing 6000 tons, the "Nankun" platform is designed for high efficiency in harnessing wave energy. Under full load conditions, it is capable of generating 24,000 kWh of electricity per day, demonstrating a remarkable overall conversion efficiency of 22% [51]. This breakthrough in wave energy technology marks a significant milestone in the development of renewable energy solutions.


(**a**) (**b**)

Figure 4. Photos of (**a**) the "Penghu" device and (**b**) the "Zhoushan" device.

Figure 5. China's first megawatt floating wave power generation device "Nan Kun".

The "JIDA I" oscillating point-absorption wave energy generator, developed by Jimei University (JMU), was designed for wave energy conversion and power generation on a floating platform [52,53]. Sponsored by the Special Fund Plan for Marine Renewable Energy (SFPMRE) in 2011, this device underwent sea trials near Xiaodeng Island in June 2014, operating in a water depth of 15 m [54]. The platform, resembling a ship, had overall dimensions of 18 m × 8 m × 2.4 m. It featured ten oscillating buoys, each with a diameter of 0.5 m and a 200 kg mass extending from the platform. The energy conversion system included two 5-kW permanent magnet generators (PMG), driven by both the oscillating buoys and a vertical axis wind turbine fixed on the platform. Following this, the "JIDA II" and "JIDA III" were successively developed, with each generation showing improvements and advancements [55].

On 20 September 2024, the "JIDA IV" self-propelled hybrid-flow aerodynamic wave energy generation platform was successfully launched (Figure 6). This platform is the first domestically to achieve a power generation efficiency of 100 kW. Measuring 21.6 m in length, 13.25 m in maximum width, and a draft of 6.00 m, it efficiently captures wave energy and boasts a broader wave response bandwidth, improving both wave energy conversion and transmission efficiency. Furthermore, the platform is equipped with a comprehensive oil-electric hybrid drive system, a rudder, and a steering mechanism, allowing it to navigate freely at a set speed on the sea. It can flexibly reach any desired maritime area for power generation and effectively avoid typhoons.

Figure 6. The "JIDA IV" self-propelled hybrid-flow aerodynamic wave energy generation platform.

Based on the concept of oscillating bodies absorbing wave energy, the team at Harbin Engineering University has developed a variety of wave energy devices [56–58]. Liu et al. [59] proposed an array of floating point-absorbing WECs connected to a semi-submersible bottom-moored platform, analyzing the hydrodynamic interactions and optimizing array layouts, wave direction, absorber separation, and PTO damping to enhance power production efficiency in intermediate water depths. In an experimental manner, Zheng et al. [60] tested a wave energy converter with two floating bodies, analyzing the impact of wave height, wave period, PTO damping, and mass ratio on dynamic performance and energy conversion efficiency. Inspired by the UC-Berkeley wave-energy extractor [61,62], Reabroy et al. [63] designed a "Dolphin" wave energy converter integrated with a fixed breakwater (Figure 7) and investigated its hydrodynamic and power capture performance using CFD simulations and experimental testing. The results demonstrate that the "Dolphin" WEC, with optimized parameters and integration with a breakwater, achieves better motion response (RAO) and power efficiency, with a maximum power efficiency of 0.376 under specific wave conditions. In October 2020, the prototype successfully operated in the South China Sea for 13 months, providing power to some equipment on offshore platforms [64]. During this period, it withstood seven typhoons and operated continuously without any malfunctions for over six months.

Figure 7. Sea trial test of WEC [64].

China has made significant advancements in wave-activated body wave energy converters, with notable developments such as the "Penghu" aquaculture net cage, the "Zhoushan" wave energy system, and the megawatt-scale "Nankun" platform. The "JIDA" series has evolved to improve efficiency and mobility, while research institutions have explored innovative designs, including hybrid platforms and breakwater-integrated WECs. These efforts highlight China's progress in enhancing wave energy conversion efficiency, device durability, and large-scale deployment. Meanwhile, scholars have also contributed to the theoretical research on Wave-activated Body (WAB) type wave energy converters. For instance, Li et al. [65] tested a novel floating two-body wave energy converter, optimizing its design for enhanced energy capture by analyzing its dynamic response, key parameters, and the effects of fluid viscosity and mooring stiffness on performance. Zhou et al. [66] investigated the performance of a negative stiffness mechanism (NSM) in multi-module hinged wave energy converters, demonstrating its ability to enhance wave energy capture efficiency by improving pitch response and broadening the capture band in irregular waves.

To provide a comprehensive overview of China's advancements in wave energy conversion technology, Table 1 summarizes the key wave energy conversion devices developed in China. The table highlights their advantages, limitations, current application status, and Technology Readiness Level (TRL). These devices demonstrate significant progress in energy conversion efficiency, structural stability, and adaptability to marine environments. However, challenges such as high initial costs, complex maintenance requirements, and performance limitations under varying wave conditions remain key obstacles to large-scale deployment. Understanding these aspects is crucial for guiding future research and development efforts toward more efficient, cost-effective, and commercially viable wave energy solutions.

Table 1. Summary of wave energy conversion devices developed in China: advantages, challenges, and application status.

Name	Advantage	Disadvantage	Application Status	TRL
BD102G	1. Lower manufacturing costs; 2. Higher power generation efficiency	Limited to specific locations with suitable wave conditions	Widely deployed in China's coastal areas	9
"Huaqing"	1. Increases air turbine efficiency by 25% compared to existing global technologies; 2. Expands frequency response range by 70% 3. Reduces anchor chain load by 85%	1. Complex mechanical and hydraulic systems; 2. Higher initial and maintenance costs compared to other OWC systems	Successfully launched on 26 January 2025, in Jiangmen City	8
"Penghu"	1. Provides a substantial volume of aquaculture water and accommodates up to 20 residents; 2. Integrates a solar power generation system	1. Higher construction and maintenance costs; 2. Low wave energy conversion efficiency under small wave conditions, affecting overall energy supply stability	Commissioned for operation in 2019	8
"Zhoushan"	1. Excellent structural stability; 2. Equipped with a dual hydraulic PTO system, ensuring high energy capture performance	1. High initial capital and maintenance costs; 2. Low wave energy conversion efficiency under small wave conditions, impacting energy supply stability	Commissioned in 2020	7
"Nankun"	1. Generates a substantial amount of power; 2. Under full load, it produces 24,000 kWh daily with a 22% conversion efficiency	1. High initial capital and maintenance costs; 2. Significant energy loss in the three-stage conversion process	Trial operations conducted in Zhuhai in 2023	7
"JIDA I"	1. Easy to install, maintain, and expand; 2. Operates stably in harsh marine environments, withstanding challenges such as strong winds, waves, and salt spray corrosion	1. Low energy conversion efficiency in large-period wave conditions; 2. High initial capital and maintenance costs	Underwent sea trials near Xiaodeng Island in June 2014 at a water depth of 15 m	7
"JIDA IV"	1. Features a broader wave response bandwidth, enhancing both wave energy conversion and transmission efficiency; 2. Capable of autonomous navigation to avoid typhoons and reach desired maritime locations for power generation	1. Higher construction and maintenance costs; 2. Reliability under extreme sea conditions requires further improvement	Successfully launched in 2024	7

4. Development Trend of Wave Energy Generation Devices in China

In the past, wave energy generation devices faced issues such as low efficiency, limited adaptability, and short operational lifespans. To overcome these challenges, researchers have persistently sought innovations in both device technology and development methodologies [2,7,17,67–69]. In the future, the advancement of wave energy generation technology will no longer be confined to the study of individual devices; instead, it will move towards multi-degree-of-freedom systems [70–73], array-based generation [55,74–76], multi-energy complementary coupling [50,77,78], and the utilization of multifunctional integrated platforms [72,79–82]. Furthermore, the application of intelligent technologies in marine energy conversion devices will emerge as one of the key trends in future development [50].

4.1. Multi-Degree-of-Freedom System

Most traditional wave energy conversion devices typically capture energy in a single degree of freedom. However, research indicates that multi-degree-of-freedom devices are more efficient in harnessing wave energy. Increasing the number of degrees of freedom can significantly enhance energy capture efficiency [3,83]. Currently, research on multi-degree-of-freedom wave energy devices remains primarily in the theoretical and experimental stages. Yet, waves in real marine environments exhibit strong randomness and irreproducibility, making simplified simulation tests unable to accurately reflect actual conditions, thus increasing the risk of device operation at sea. To better achieve multi-degree-of-freedom wave energy capture, significant progress must be made in key technologies, such as designing energy conversion bodies, coupling methods between individual bodies, and energy extraction systems.

4.2. Arraying of WECs

The array-based layout enables wave energy devices to capture wave energy comprehensively, continuously, and uniformly under varying sea conditions, thereby achieving large-scale, stable power output and enhancing energy conversion efficiency [84,85]. This arrangement not only boosts power generation efficiency but also significantly reduces the production cost of electricity per unit. Consequently, the array layout provides more favorable conditions for the commercialization of wave energy generation, especially in the context of large-scale power generation needs. Vervaet et al. [86] conducted experimental tests on a single heaving point absorber WEC to validate numerical models and optimize WEC array performance, laying the groundwork for future multi-WEC array studies. Giassi and Goteman [87] presented a genetic algorithm-based optimization tool for wave energy design, optimizing single point-absorber WEC parameters and array layouts to maximize energy production while minimizing destructive interactions. Devolder et al. [88] used OpenFOAM-based CFD simulations to analyze the hydrodynamics of floating point absorber WEC arrays, validating the numerical wave tank model against experimental data and demonstrating its accuracy for fluid-structure interaction studies.

Compared to individual wave energy devices, which have smaller capacities and higher generation costs, making it difficult to meet the demand for large-scale power generation, the modular design of wave energy conversion devices allows for flexible expansion into megawatt-level arrays, further increasing the system’s scale and the power generation capacity of individual devices [32,89,90]. By designing the array layout based on the environmental conditions of different sea areas, it is possible to effectively expand the scale of wave energy generation and improve the system’s overall efficiency.

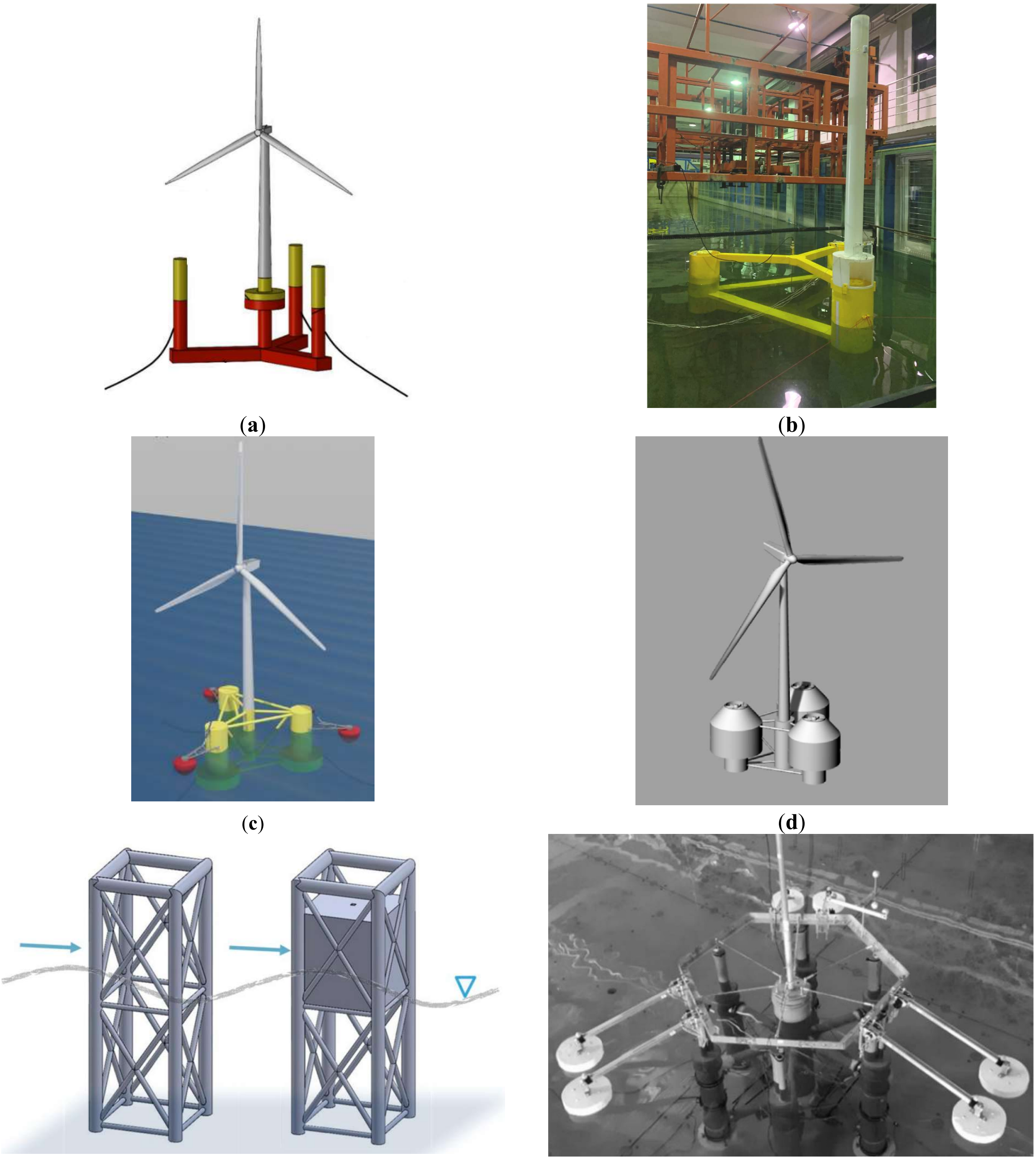
4.3. Multi-Energy Complementary Coupling

The coupling of wave energy with other marine renewable energy sources, primarily wind energy, has become a key research focus in the field of marine energy [91,92]. By combining wave and wind energy through joint development and synergistic utilization, it is possible to significantly enhance the utilization of marine space while reducing the costs associated with infrastructure such as subsea cables, thereby lowering the unit generation cost. Wave energy devices can be integrated with floating wind turbine platforms, or wind turbines can be coupled with floating wave energy devices for joint power generation. Additionally, wind turbines and wave energy devices can be strategically arranged and coordinated in nearby areas to achieve a synergistic power generation model combining offshore wind and wave energy. Ustinov and Shafhatov [93] explored the benefits of integrating wave energy converters with offshore wind turbines, analyzing system reliability improvements and optimal topology while considering shadow effects from wave installations. Hu et al. [94] investigated the impact of geometric asymmetry and partial reflecting walls on the power performance of heaving-body WECs, providing design recommendations to enhance wave power absorption efficiency in various deployment conditions. Cheng et al. [95] proposed a novel combined wind and wave energy system integrating a spar-type floating vertical axis wind turbine (VAWT) with a torus-shaped point absorber WEC. The study evaluated the power performance and dynamic behavior through fully coupled simulations under turbulent wind and irregular waves. It demonstrated that the WEC increases total power output while having minimal impact on the operation of the VAWT. The results highlight the potential of this combined concept in reducing the cost of energy (CoE) for offshore renewable systems. Additionally, Reducing the complexity of technological development, advancing theoretical research, and making coupled devices practical remain critical challenges that need to be addressed [79,80].

4.4. Multifunctional Integrated Platform

In the future, wave energy generation devices may progressively evolve into multifunctional offshore platforms, becoming smart marine renewable energy platforms that integrate wave energy generation, aquaculture, tourism, environmental monitoring, and other functions [80,92] (see Figure 8). The high adaptability of these integrated platforms will enable them to transcend traditional nearshore development models, extending into deeper ocean regions. By utilizing array-based platform layouts, the range of marine resource development can be expanded, further enhancing the efficiency of wave energy generation.

Moreover, with technological advancements, wave energy devices will gradually be deployed in remote islands and other special areas, becoming a key solution to address energy and water resource challenges in these regions [79,96]. For example, Perez-Collazo et al. [97] investigated a hybrid wind-wave energy system integrating an oscillating water column (OWC) with a monopile substructure through a scaled experimental campaign, demonstrating its potential for efficient wave energy conversion and favorable wave-structure interactions. Howe et al. [98] presented a proof-of-concept for a floating breakwater integrated with OWC wave energy converters, highlighting the influence of device spacing on energy extraction and offering insights into the feasibility of offshore multi-purpose structures. Konispoliatis et al. [99] developed a multi-purpose floating tension leg platform (TLP) for combined offshore wind and wave energy, integrating oscillating water column devices with a wind turbine, and presented an integrated design approach validated through hydrodynamic model tests. Ding et al. [100] investigated the dynamic behavior of integrated floating energy systems (IFES) combining floating offshore wind turbines (FOWTs) with oscillating wave energy converters, showing that appropriate WEC layouts improve platform stability and increase energy output by up to 6.07%. By integrating electricity generated from wave energy into island grids, the power needs of island residents can be effectively met. Simultaneously, the desalination capabilities of the platform will provide a stable supply of freshwater for island inhabitants, truly realizing the concept of "marine energy for marine use" and promoting the comprehensive application of marine energy.



(**a**) (**b**)

(**c**) (**d**)

(**e**) (**f**)

Figure 8. Multifunctional integrated platforms. (**a**) A WEC-wind turbine integrated model [79], (**b**) A FOWT-OWC platform [91], (**c**) DeepCwind-Wavestar-Combined (DWC) system [101], (**d**) A multi-purpose floating structure [102], (**e**) A jacket type structure installed with OWC converter [103], (**f**) A floating hybrid platform with six WECs [104].

4.5. Intelligent Technology

With the continuous advancement of wave energy harvesting technology, the application of artificial intelligence (AI) in wave energy devices has become a crucial means to enhance energy capture efficiency and adaptability. The efficiency of wave energy collection is often affected by the complexity and unpredictability of sea conditions, and traditional physical modeling methods often struggle to cope with dynamic changes. In contrast, AI is capable of processing high-dimensional complex data and optimizing the design and operation of wave energy devices in response to changes in the marine environment [105]. Through machine learning algorithms, AI can analyze and predict wave patterns, assisting devices in adapting and adjusting operational strategies to ensure optimal energy capture efficiency under varying sea conditions. Mishra et al. [106] modified the Hammerstein framework to improve heave force prediction for wave energy converters in irregular waves by introducing a Bouc-Wen model and a nonlinear Kolmogorov-Gabor polynomial structure, reducing prediction errors by up to 70% and improving hydrodynamic force predictions by up to 38%. He et al. [107] optimized a square array of four cylindrical heaving-buoy wave energy converters by considering parameters like buoy radius, draft, damping, and spacing, using differential evolution for multi-parameter optimization, achieving high energy capture efficiency in both regular and irregular waves. Additionally, AI technology can optimize the structural design of devices, using deep learning to analyze the performance of different design configurations and identify the most suitable setup for specific marine conditions [108]. Furthermore, AI can be employed for real-time monitoring of device operations, fault prediction, and maintenance planning, thereby reducing operational and maintenance costs while extending the device's lifespan. Through big data analysis and pattern recognition, AI can uncover underlying patterns in the marine environment, helping wave energy devices make more informed deployment and optimization decisions [80,109].

5. Conclusions

This paper provides a comprehensive review of the latest research achievements in the development of wave energy in China, focusing on the technological advancements of wave energy conversion devices and future development trends. The research reveals that China has made significant breakthroughs in the research, development, and testing of wave energy generation devices. The development of wave energy conversion devices is diversifying, with oscillating water columns, overtopping, and oscillating body devices, each having unique characteristics. Among these, oscillating water column and oscillating body devices have more mature technologies and show great potential for applications in multi-degree-of-freedom systems, array-based layouts, and multi-energy complementary coupling power generation.

Looking forward, several key perspectives and future directions exist for developing wave energy conversion (WEC) technologies. First, the integration of WECs with other renewable energy sources, such as offshore wind and solar power, presents significant opportunities for multi-energy complementary systems that can improve efficiency and stability in power generation. Second, ongoing advancements in the design and optimization of WECs will lead to more efficient devices with better energy capture capabilities, especially in harsh marine environments. Moreover, exploring innovative array-based configurations of WECs and improving their scalability will be crucial to realizing the full potential of wave energy. Finally, future developments should focus on enhancing these systems environmental impact assessments and long-term durability to ensure their sustainability in commercial applications.

Based on the review, these perspectives offer a roadmap for future research and technological innovation in wave energy, paving the way for more efficient and sustainable solutions in marine renewable energy.

In conclusion, marine energy holds immense development potential as a clean and renewable energy source. With continuous technological innovation and policy support, marine energy is expected to play a crucial role in the future energy structure and significantly contribute to achieving global sustainable development goals.

Author Contributions

Conceptualization, B.Z. and W.P.; Writing—Original Draft Preparation, B.Z. and Y.L.; Writing—Review & Editing, W.P.

Ethics Statement

Not applicable.

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Not applicable.

Data Availability Statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on request.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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