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Review

Research on Wave Energy Converters

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Abstract: With the acceleration of the global warming process, the clean energy crisis is becoming serious; conventional energy is unlikely to solve the current crisis, so people pay attention to new energy. As wave energy is widely distributed, renewable, and clean, hundreds of wave energy converters emerge. In order to understand the research progress of wave energy converters better, this paper divides wave energy converters into overtopping type, oscillating water column type, and oscillating body type according to the working principle and divides the oscillating body type into oscillating float type and oscillating pendulum type by different ways of energy capture. Based on the classification, various types of engineering cases, physical tests and digital simulation, and other academic research results are summarized, especially the generation power and energy conversion efficiency of various devices, and some shortcomings and suggestions are put forward, hoping to provide help for readers to study wave energy generation converters.

Keywords: wave energy converter; overtopping; oscillating water column; oscillating body; captured energy efficiency; conversion efficiency; power generation efficiency

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1. Introduction

To face the growing energy crisis, the world is developing green energy sources. Coincidentally, wave energy has the advantage of being widely distributed, renewable, high-energy density and clean [1]. Therefore, many researchers have worked on wave energy generators and have obtained many results.

Since the advent of wave power generation devices, there have been more than 300 kinds of wave power generation converters, more than 6400 patents for wave energy conversion technology [2], and numerous engineering projects, such as, “Kaimei” [3], “Mighty Whale” [3], “Pelamis” [4], and “Wan Shan” [5]. Figure 1 gives the development process of the wave energy power generation project. In 1799, the French Girard and Son invented an “air wave machine” [6]. In 1910, a pneumatic wave power station was built in Brassack, France [7]. In 1940, Yoshio Masuda, the founder of the oscillating water column device, designed the world’s first floating oscillating water column device “Kaimei” [8]. Yoshida Yoshio, invented the first commercial wave power generation system, the wave energy converter for optical buoys at sea in 1965 [9]. In 1975, a 1kW wave energy buoy was tested in Chengshan, China [10]. In 1978, the kilowatt-level air turbine wave power buoy was successfully developed and tested in Zhoushan Islands, China [10]. -G1-T, the earliest Oscillating float WEC, was tested in Tokyo Bay in 1980 [11]. In 1986, Norwegian AS Company built the world’s first fixed overtopping wave energy converter-TAPCHAN, with an installed capacity of 350 kW [12]. In 1987, Japan developed a floating oscillating water column device- “Mighty Whale” [13]. Pico was built in Portugal with an installed capacity of 400 kW in 1991 [14]. In 1992, Stephen Salter invented the Swing Mace [15].

The UK began to build the LIMPET 500 in 1998 [16]. In 1999, The 100 kW pendulum wave power station was built by the Institute of Marine Technology of the State Oceanic Administration of Tianjin (Tianjin, China) [10], Canada Finavera Renewable Energy Co., Ltd. (Vancouver, BC, Canada) developed AquaBuoy in 2000 [17]. In 2001, the British proposed the Oyster buoyancy pendulum device and carried out sea trials in 2009 [18]. Denmark developed the floating overtopping wave energy converter "“Wave Dragon” [19], the OE Buoy floating oscillating water column device was developed by the University of Cork and Ocean Energy in the United Kingdom [20], Finland’s AW energy company developed the Wave Roller in 2003 [21]. In 2004, a Gyro WEC with a rated power of 5.5 kW was successfully developed [22]. In 2005, Sweden began to develop 350 kW OWEL [20]. In 2005, Aalborg University in Denmark and Langlee Wave Power AS in Norway jointly developed Langlee WEC [23], the U.S. ocean power technology company developed’ Power Buoy [24]. In 2009, Bio Wave was jointly developed by Australia’s Bio Power Systems and Germany’s Siemens [25]. Sweden developed 350 kW OWEL, and began to carry out sea trials in 2011 [20]. In 2015, “Wanshan” wave energy power generation device was put into operation, with an installed capacity of 120 kW [5]. On 1 November 2022, AWS captured an average power of more than 10 kW and a peak power of 80 kW under moderate wave conditions, which exceeded the developer’s own prediction by 20% [26]. Figure 2 shows “Mighty Whale”, “Wanshan” and “Pelamis” WEC.

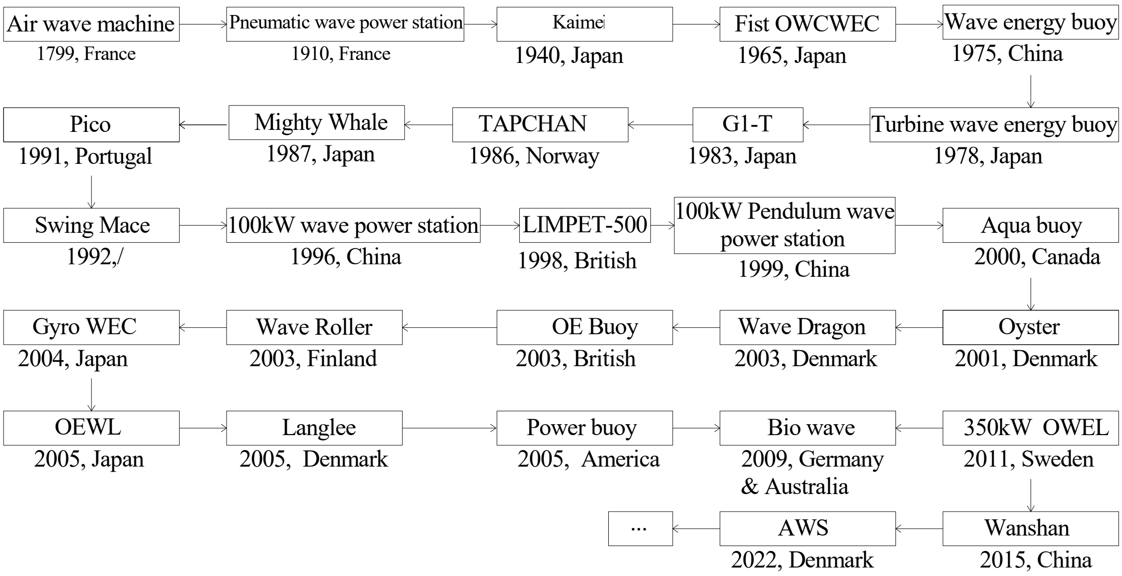
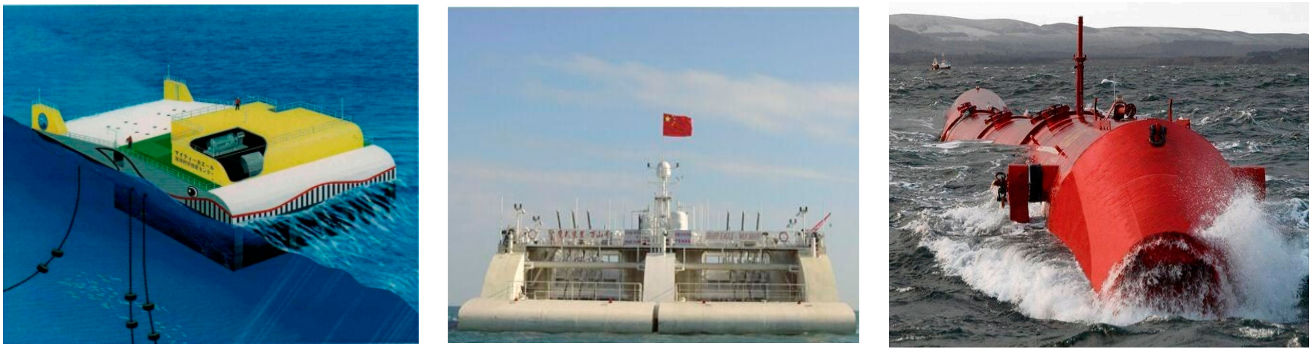


Figure 1. WEC projects development process. Note: The years marked in the figure is the start time of the project, and projects within the same year are not listed successively.



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

Figure 2. Projects of WECs. (**a**) Mighty Whale WEC [20]. (**b**) Wan Shan [5]. (**c**) Pelamis WEC [20].

In addition, academic research does not stop. People are constantly exploring different WECs through physical experiments or numerical simulation methods in order to find stable and highly efficient WECs.

Many scholars have already reviewed WECs. For example, Lindroth and Leijon [3] reviewed the test methods of classical engineering examples. Han et al. [27] analyzed 31 references by classifying WECs according to wave energy primary, intermediate, and secondary conversion. Wang et al. [28] reviewed 16 references and classified them by power take-off (PTO) systems. Liu et al. [29] introduced domestic and international engineering examples of oscillating water column wave energy converters (OWCWECs). Chen et al. [30] reviewed the research progress of direct wave energy harvesting. Shi and Liu [31] introduced the classic engineering cases of overtopping type (OWEC), oscillating water column type (OWCWEC), and oscillating body type (OBWEC). Zhang et al. [9] referred to 92 studies, mainly analyzed the basic structure, working principle, and PTO of WECs, and proposed to construct a comprehensive multi-indicator model using hierarchical analysis. Chen et al. [32] compared and explained the demonstration wave energy power generation projects and summarized the power generation control technology in more detail. However, there are few reviews of the academic research on WECs. Compared with the previous review, this paper increased the amount of research on wave energy converters by including articles from the past five years. Not only the classic engineering examples are classified in this paper, but also the academic research results of wave energy converters are classified; in particular, the energy conversion efficiency of each stage in the reference is analyzed so readers can understand the performance of various converters more clearly.

2. Classification and Working Principle of WEC

Now, there are many methods to classify WECs. For example, according to the fixed mode, they can be divided into fixed type and floating type. On the basis of the energy collection, they can be divided into duck type, pendulum type, raft type, overtopping type, oscillating water column type, and oscillating float type [28]. In accordance with the installation position, they can be divided into shore-based, near-shore, and offshore. According to the working principle, it can be divided into overtopping type, oscillating water column type, and oscillating body type [33]. According to the power take-off, WECs can be divided into hydraulic motor type, air turbine type, hydraulic turbine type, gear type, linear motor type, magnetic fluid motor type [33], and so on. This paper overviews WECs in accordance with the working principle, dividing WECs into OWEC, OWCWEC, and OBWEC. Then, according to the different ways of energy capture, OBWEC is divided into oscillating float WEC (OFWEC), oscillating pendulum WEC (OPWEC), and other types of OBWEC (OTWEC). The classification can be seen in Figure 3. No matter what kind of WEC type it is, the wave energy will be converted into electrical energy. Basically, the WEC has to go through three stages of energy conversion: in the first stage, it converts the wave energy into mechanical energy or air energy, etc.; in the second stage, it converts the energy absorbed in the first stage into usable mechanical energy through a power take-off (PTO); in the third stage, it converts the energy obtained in the second stage to electrical energy through the generator [9]. The conversion process can be seen in Figure 4. In this paper, the energy conversion efficiency of the three stages respectively named captured energy efficiency (η_1), conversion efficiency (η_2), and power generation efficiency (η). It should be noted that not all converters require tertiary energy conversion; some only need two stages, the first and the third, to complete the entire process.

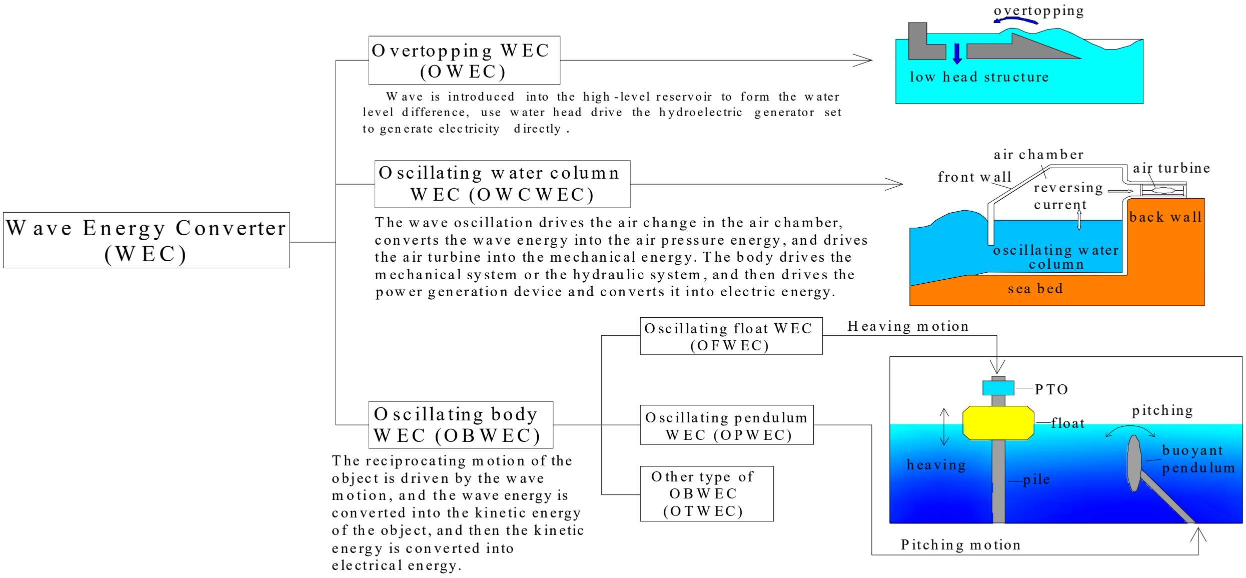


Figure 3. Classification of wave energy converters [31,34,35].

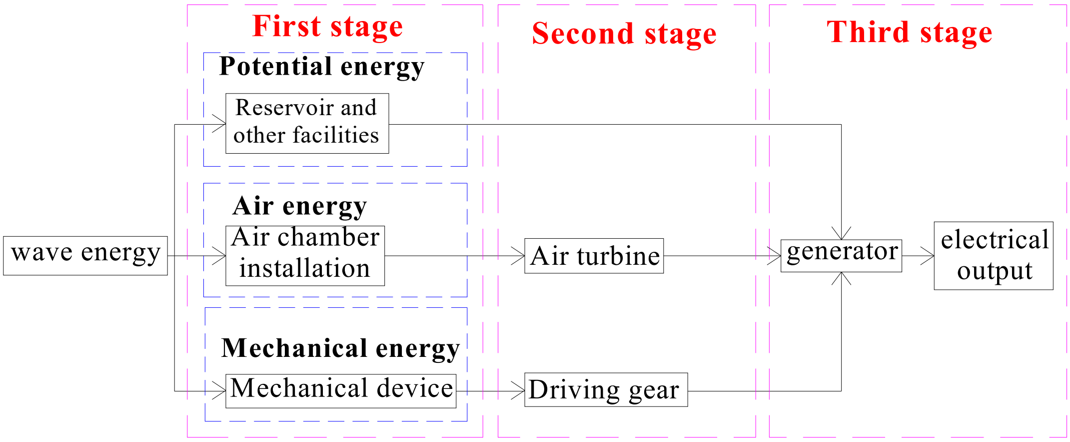


Figure 4. Different energy conversion stages.

2.1. *Overtopping Wave Energy Converter (OWEC)*

The overtopping wave energy converter (OWEC) is a converter that introduces waves into a high-level reservoir to form a water level difference and finally uses the water head to drive the hydropower unit to generate electricity directly [36]. OWECs are mostly fixed and built-in coastal or near-shore areas. For example, the world’s first fixed OWEC-TAPCHAN near the MOWC power station, with an installed capacity of 350 kW [12]. Norway has established an OWEC SSG combined with a breakwater [37]. The converter was equipped with a multi-layer water tank; seawater can be stored at different heights [9]. Besides the fixed type, there are also floating types. The “floating WEC ship” developed by the Swedish Marine Power Company is a floating OWEC [38]. In 2003, Denmark developed the floating OWEC “Wave Dragon” [19]. Figure 5 shows the famous OWEC Engineering examples: TAPCHAN [9] and OWEC SSG [37].

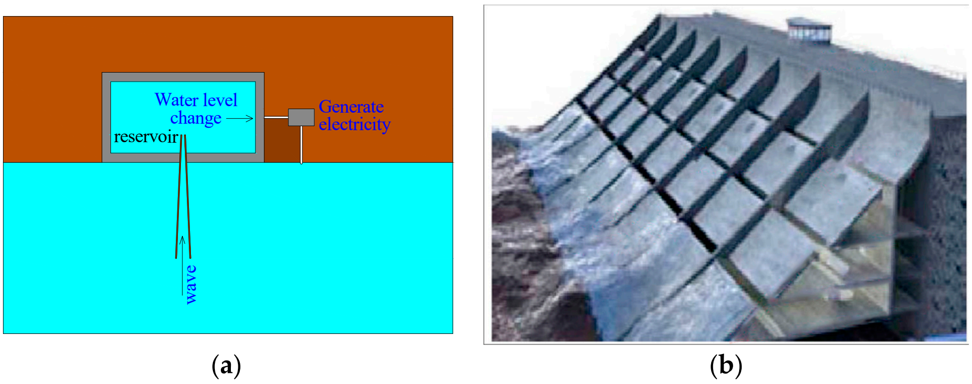


Figure 5. Engineering example of OWECs. (**a**) TAPCHAN [9]. (**b**) OWEC SSG [37].

Huang et al. [39,40] designed a saucer-like OWEC and set a sea trial. Physical experiments found that the amount of overtopping increases with the increasing wave height (H), and the overtopping amount decreases with the increase in freeboard height. From the sea trial results, it was found that when H was 1.0–1.5 m, the average output power was about 6.2 kW, and the sea was continuously operated for 116 h, with a cumulative power generation of more than 400 kWh. Chen et al. [41] conducted a physical model test using a scale of 1:25 to analyze the hydrodynamic performance of OWEC. They found that the maximum wave pressure appeared at the bottom of the ramp. The overtopping amount showed a decreasing trend, with an increase in wave steepness and relative top height, and the maximum captured energy efficiency (η_1) was close to 18%. Yang et al. [42] adopted a physical experiment to analyze the overtopping and force of OWEC under the condition of regular and irregular waves. It was concluded that the overtopping amount increased with the increasing period (T). However, the increased R (the ratio of freeboard height to wave height) had a decreasing trend. Xu et al. [43] and Ma et al. [44] studied the mechanical characteristics of the stratified slope overtopping wave energy power generation device (DR-OWEC), which was composed of upper reservoir, upper wave plate, lower reservoir, and lower wave plate. The study found that the wave load on the upper wave surface of the device increases with the increase in water depth (h) and wave period (T) with the physical test. In reference [44], the FLOW-3D numerical simulation method was used, obtaining that regardless of the water level, when the wave height was constant, the overtopping amount of the upper and lower layers decreased with the increasing wave steepness. At different water levels, the wave pressure on the upper and lower wave surfaces of the converter decreases from the bottom to the top. The impact pressure increased from the bottom to the top and gradually increased with the increase in wave height. Interlayer water turbulence was not conducive to the converter's capturing energy. Dong Soo et al. [45] studied the overtopping structure (FOWEC) of wave-proof and wave energy converters through physical experiments. FOWEC was divided into two parts. An impervious slope with a slope of 1:3 was set on the wave-facing side. The top of the slope was higher than the water surface, and the slope was followed by a rectangular flume. There were drainage holes at the bottom of the flume. From the energy calculation results of the literature, the maximum power could reach 50 mW.

Liu et al. [46] numerically simulated the effects of different wave conditions, submerged depth, and freeboard height on the wave energy converter. They found that the overtopping amount decreased with the increase in freeboard height; the overtopping performance under long-period waves was better than that of short-period waves in a certain range (similar to the results of reference [42]). You et al. [47] used FLOW-3D to analyze the force of the structure of the sliding-baffle OWEC. It was found that the position on the slope with the same height as the water depth was the first impacted by the wave, and it spread up and down when H increased. Based on the data, the slope force exceeded 120 N. Liu et al. [48] used numerical simulation to analyze the structure of the disc-shaped OWEC and concluded that the overtopping performance could be promoted by having more guide vanes (12 guide vanes), a slope ratio of 1:2, a dry-docking height of 0.1 m, and a return plate length of 0.15 m. The slope-type OWEC with double reservoirs [43,44], the floating OWEC [45], the sliding-baffle OWEC [47] and saucer-like WEC [48] are shown in Figure 6.

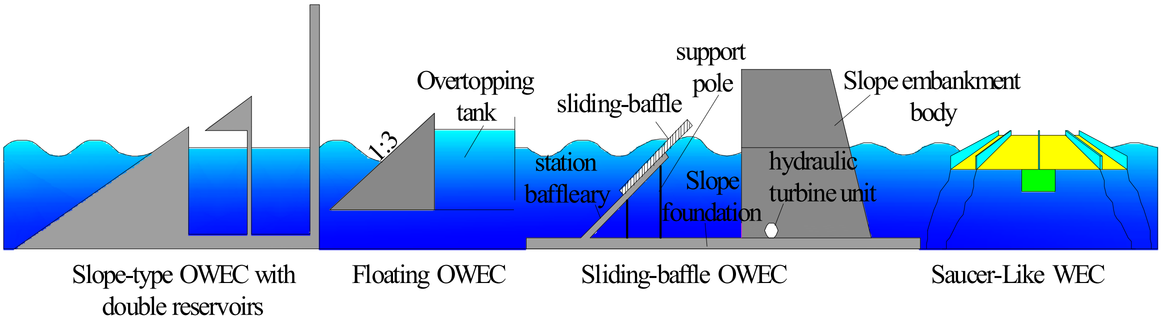


Figure 6. Overtopping WEC converters [43–45,47,48].

Fixed OWECs are constructed in coastal or near-shore areas, which are easy to build and maintain. However, the energy conversion efficiency is lower due to the installation location. It is also constrained by the topography of the coastline, tidal range, and coastal protection. Floating OWECs can be built in deep-sea areas, which are less affected by tides, but the investment is larger. From the research results, there is little research on power generation efficiency, and the captured energy efficiency (η_1) in the reference was only 18%.

2.2. Oscillating Water Column WEC (OWCWEC)

Yoshio Masuda first proposed the concept of oscillating water column WEC (OWCWEC) in the 1940s [9]. OWCWEC generally includes a partially water-entry air chamber (opened below the water surface). Under the action of waves, the air inside the air chamber converts wave energy into air energy (the first stage of energy conversion). Then, the compressed air drives the air turbine to convert it into mechanical energy (the second stage of energy conversion). Last, the reciprocating motion of the body drives the mechanical system or hydraulic system and drives the generator to convert it into electrical energy (the third stage of energy conversion), completing the three-stage energy conversion [35]. In 1965, the world's first OWCWEC navigation buoy was built. Subsequently, OWCWEC developed continuously and became the most widely used WEC in the world. Japan's "Kaimei" was the first large floating OWCWEC [4]. Japan's "Mighty Whale" [13], "LIMPET OWCWEC" in Britain [16], "Pico OWCWEC" in Portugal [14], "Oceanlinx" in Australia [49,50], Ireland's OE Buoy [51], Portugal's Spar Buoy [52], Norway's N2 buoy, Sweden's IPS buoy, and Japan's BBDB all belong to OWCWEC. We can see the examples of OWCWECs like LIMPET WEC [14], LIMPET WEC [49] and Pico WEC [50] in Figure 7.

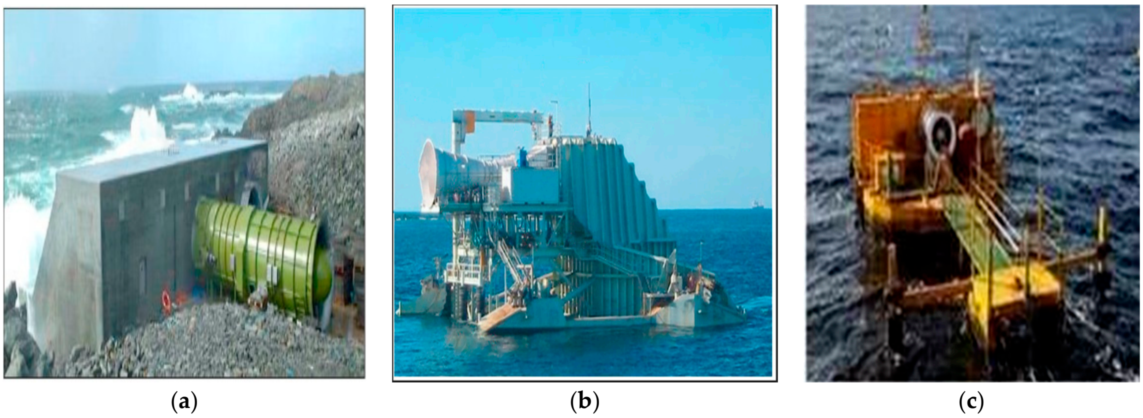

(**a**) (**b**) (**c**)

Figure 7. Different OWCWECs. (**a**) LIMPET WEC [14]. (**b**) LIMPET WEC [49]. (**c**) Pico WEC [50].

OWCWEC is a relatively popular WEC, and there are many related studies. This paper classifies and describes it from two aspects: experiment and numerical simulation.

In terms of the experiment aspect, Gao et al. [53] carried out the physical model experiment of the active pneumatic WEC in the still water tank in 1983. The working principle of the converter was expounded, and the wave energy conversion efficiency equation was deduced, but the experimental results were not mentioned. Shi et al. [54] conducted a physical experiment to study the effect of air turbine pressure drop on the energy conversion of OWCWEC. It was concluded that the output energy of the air chamber increased with the increasing period, but the wave energy conversion efficiency of the air chamber gradually decreased with increasing incident wave height. When H was 9.38 m, T was 2.0 s, the airflow rate was 8.64 m/s, and the maximum captured energy efficiency (η_1) was 28.87%. Fang et al. [55,56] carried out experimental research on wave energy extraction from floating breakwaters with asymmetric pneumatic chambers. It proved that generating efficiency in the first chamber occupied more than 85% of the total, and the maximum captured energy efficiency (η_1) was about 30%. Zhao et al. [57] compared the single-chamber, double-chamber, and three-chamber devices. The maximum efficiency of the three-chamber device was slightly better than that of the double-chamber OWC breakwater, and the captured energy efficiency (η_1) of the three-chamber was 55%. Bao et al. [35] studied the force characteristics of the front baffle of the U-shaped OWCWEC through physical model tests. It was found that the pressure changes on the inner and outer walls of the front baffle were consistent with the wave period, and the pressure on the same side changed synchronously, but there was a phase difference between the pressure changes on both sides. Meng et al. [58] designed and manufactured a horizontal rotor WEC and carried out a physical model experiment to study the influence of the shape and installation height of the lifting plate on the stability of the converter. The stability of the square and chamfered lifting plates was better, and the optimal installation distance was between 20 and 30 cm. According to the sea test results, the power generation efficiency (η) was 21.33%. Chen [59] studied the use of caissons as oscillating water column wave energy conversion devices. The effects of different chamber sizes, wave heights, wave periods, and opening sizes on the captured energy efficiency were analyzed and calculated. The efficiency decreased with the increase in wave height and increased first and then decreased with the increase in period. The captured energy efficiency (η_1) reached about 32% (when T was 1 s, H was 0.04 m).

In terms of numerical simulation, Shi et al. [60] studied the OWC chamber based on the VOF model and optimized the shape parameters of the chamber to improve the airflow velocity and energy conversion. The calculation results were compared to the experimental results to verify the accuracy of the numerical method. Liu et al. [61] used the Fluent software to simulate the three-dimensional numerical simulation of the impact turbine of OWCWEC, analyzed the influence of the outer diameter gap and hub ratio on the working performance of the turbine, studied the distribution of the surface pressure of the moving blade and the airflow, and compared it with the experimental results to verify the effectiveness of the numerical method. Liu et al. [62] used Fluent to conduct a three-dimensional simulation analysis of the impact turbine of the OWCWEC, and the maximum turbine efficiency (η_2) was about 45%. Ji et al. [63] also used numerical methods to simulate the three-dimensional OWC and compared it to the two-dimensional and experimental results to verify the correctness of the method. It was considered that the gas chamber structure of OWC had better working performance and higher energy conversion efficiency under the condition of long period (T = 6.0–8.0 s), but the energy conversion efficiency was not studied. Du et al. (2016, 2017, 2019) [64–66] established a theoretical calculation model for OWCWEC, used Fluent to simulate OWCWEC based on the piezoelectric effect, and obtained that the maximum output voltage was about 0.47 V, and the maximum deformation of the piezoelectric plate was about 3 m. Wang et al. [67] optimized the OWC structure by adding a parabolic breakwater in the front of the gas chamber or installing a guide plate in it. The numerical simulation and physical test methods were used to study the relative amplitude change of the parabolic surface diameter, the focus position and the combination of the air chamber with or without the guide plate. It was found that when the parabolic focus was located in the center of the air chamber, the surface diameter was 5 m, and the guide plate could collect the wave energy better under a T of 6 s. Based on the CFD numerical method, Wang [6] studied the effects of different blade thicknesses, blade rotation angles and blade incidence angles on efficiency. When the blade rotation angle was $-6°$, the turbine efficiency (η_2) was up to 57%. Yang et al. [68] simulated the influence of different rotor blade consistencies on the steady state of the OWC radial air turbine. When the rotor blade consistency was 2.34, and the inlet velocity was -5 m/s, the peak efficiency (η_2) reached 39.7% (it was 38.6% at 5 m/s). Zhang et al. [69] also used the numerical simulation method to study the influence of the thickness of the ring structure on the input coefficient, torque coefficient, and turbine efficiency of the OWC impact air turbine after the installation of the ring structure at the tip of the moving blade. It was found that the turbine efficiency (η_2) was the highest when the thickness of the ring structure was 1.1 mm, about 55%. An active pneumatic WEC [53], an OWCWEC (under physical) [54], a floating WEC breakwater [55,56], a multi-chamber OWC breakwater [57], an OWCWEC (under numerical) [65], an OWCWEC with parabolic structure and guide plate are given in Figure 8.

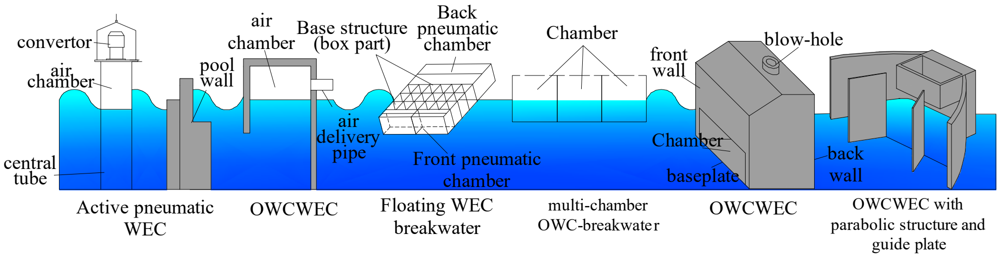


Figure 8. Research on different OWCWECs [53–57,65,68].

From the research on OWCWECs, studies using numerical simulation were more than physical experiments, and the conversion efficiency of numerical simulation was higher than that of physical experiments. The maximum captured energy efficiency (η_1) in the experiment was 55% ([57]), while the power generation efficiency was 21.33% ([58]).

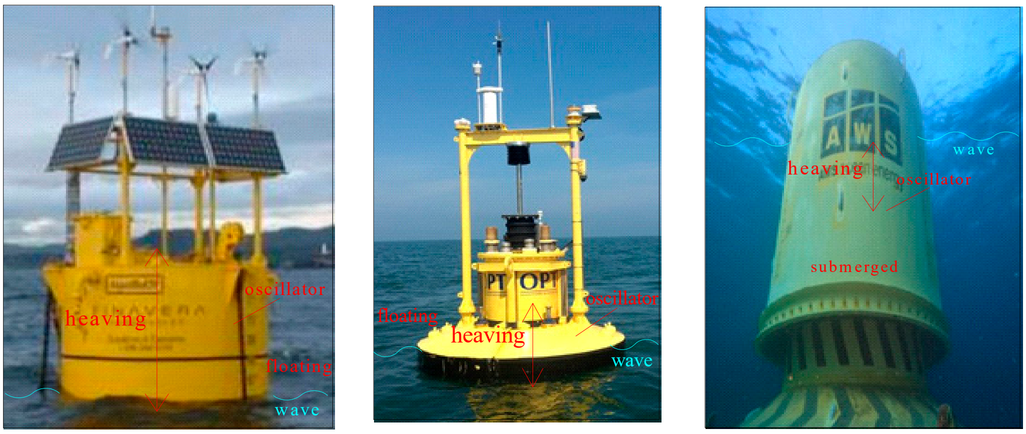
2.3. Oscillating Body WEC (OBWEC)

Oscillator refers to WECs that derive energy mainly from wave-induced oscillations' heaving or pitching motion, and oscillations may be underwater or floating [70]. It can drive the object to move back and forth through wave motion, convert the wave energy into kinetic energy, and then convert it into electric energy. The working principle of OBWEC can be seen in Figure 3. Here, according to the motion forms of the energy capture, we divided OBWEC into oscillating float type and oscillating pendulum type.

2.3.1. Oscillating Float WEC (OFWEC)

Usually, the oscillator of oscillating float WECs is submerged or floating on the water surface. The oscillator performs heaving motions, obtains energy during motion, transfers energy to the generator through the mechanical structure, and then converts it into electric energy.

The earliest OFWEC was G1-T, was tested in Tokyo Bay in 1980 [11]. In 1983, Norway tested a heaving wave energy conversion device with a spherical float [71]. The University of Uppsala in Sweden studied the WEC of the float mooring by tension and conducted a sea trial on the west coast of Sweden [72]. Finavera Renewable Energy Ltd. (Vancouver, Canada) in Canada developed "AquaBuoy" in 2000 [17]. In 2005, Ocean Dynamics Technologies developed the "Power Buoy" [24]. "L-10" was developed by Oregon State University. A 10 kW prototype was tested at sea in Newport, Oregon [73]. The Power Buoy prototype developed by OPT Company in the United States was tested in Spain; with an installed capacity of 40 kW, the converter was an axisymmetric twin-body heave system [74]. The 120 kW floating wave power station of Shandong University is also a double floating WEC [75]. The Norwegian FO3 is an array wave energy device with 21 wave energy buoys in heave motion [76]. Tianjin Haijin Ocean Engineering Co., Ltd. (Tianjin, China) and Harbin Engineering University developed a 10 kW hydraulic floating WEC [77]. In 2014, the Ocean University of China developed a 10 kW combined wave energy device and successfully carried out sea trials in Zhaitang Island, Qingdao [78]. In 2022, AWS captured an average power of more than 10 kW and a peak power of 80 kW under moderate wave conditions, which exceeded the developer's own prediction by 20% [26]. Figure 9 shows the example of OFWECs, such as Aqua Buoy [17], Power Buoy [24], AWS [26].



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

Figure 9. Engineer examples of OFWEC. (**a**) AquaBuoy WEC [17]. (**b**) PowerBuoy WEC [24]. (**c**) AWS WEC [26].

Here, we review OBWECs from the two aspects of experiment and numerical simulation/theory.

Firstly, in terms of the experiment aspect, Farshad et al. [79] designed the "Berkeley Wedge" WEC breakwater. The numerical simulation results show that the captured energy efficiency (η_1) was 96.34% when the absorption damping matched with the radiation damping of the buoy. The physical test was used to verify that when the damping ratio was 0.48, η_1 reached 82%. However, the curved surface of the converter had high requirements and was difficult to be applied in engineering. Zheng et al. [80] designed a wave energy device with a swing arm float and carried out a physical model test. It was concluded that the power generation efficiency of this device was up to 33.8% (when T was 1.8 s, H was 0.175 m). Ning et al. [81] proposed a pile-restrained WEC floating breakwater and studied the influence of draft, period and wave height on the conversion efficiency through physical experiments. It concluded that the wave height and excitation current have a great influence on the conversion efficiency. Through reasonable adjustment and configuration, conversion efficiency (η_2) can reach 24%. Shi et al. [82] studied the hydrodynamic performance and CWR under the action of wave field through the hydraulic physical model. They selected H (0.1–0.25 m) and T (1.5–2.5 s) in the test. It found that the period of oscillation was consistent with the wave period. η_1 was calculated to be about 15–25%. Liu & Chen [83] studied the captured energy efficiency (η_1) of the truncated cone-shaped float OBWEC by physical experiment and concluded that the captured energy efficiency increased with the increasing steepness. When H was 15 cm, T was 1.2–1.8 s, the horizontal wave force was about 15–18 N, and η_1 was 35.6%.

In the aspect of numerical model theory, Mao et al. [84] used the AQWA simulation to analyze the captured energy efficiency of seven kinds of oscillating bodies. They found that the trapezoidal floating body with long sides and short middle had the best energy capture effect, with an η_1 of 41.34% (H = 1 m, T = 5–7 s, γ = 3.3). However, the calculation did not consider forces other than the wave force, which may cause the result to be too large. Zhang et al. [85] used Star-CCM + to compare and analyze the captured energy efficiency of floating WEC breakwaters with a square bottom, a triangular bottom (with and without baffles), and a "Berkeley-Wedge" bottom under regular waves. It was found that when 3.0 < ω < 4.5 rad/s, the η_1 of the Berkeley Wedge converter increased to 92%. Chen et al. [86] calculated the conversion efficiency of the structure of reference by numerical simulation and compared the right angle of the pontoon with the curved angle type. They obtained that the conversion efficiency of the curved angle type was better than that of the right-angle type, and the maximum η_2 was about 45%. Ji et al. [87] used numerical methods to study the influence of the PTO damping force, wave frequency, draft, and curtain wall height on the structure similar to reference [82]. The results showed that conversion efficiency increased first and then decreased with the increase in PTO damping force, and η_2 could reach 40%. Zhao et al. [88] analyzed the influence of optimal PTO damping, relative width and relative draft on the integrated system (composed of the breakwater and oscillating buoy WEC) and found that the conversion efficiency (η_2) maximum value was 50%. Zhang et al. [89] numerically analyzed the effects of incident wave conditions, submergence depth, and PTO damping coefficient on the heave performance and energy conversion capability of the buoy. The results showed that when the PTO damping coefficient k_p was 2000, the maximum extraction power of the wave energy was 21.4 W, and the peak absorption efficiency (η_2) reached 34.2%. Ma et al. [90] used OpenFOAM to analyze the linear optimal PTO system and fixed the damping coefficient PTO system and Coulomb PTO system to study the parameter effect of PTO on the converter. The Coulomb damping model performs well in wave energy captured efficiency, and the maximum conversion efficiency (η_2) was 34.9%. Yong et al. [91] used a three-dimensional numerical flume to analyze the energy extraction of the moonpool WEC breakwater, and the maximum conversion efficiency (η_2) could reach 45%. Zhou et al. [92] studied the effects of PTO damping, asymmetry and absolute asymmetry on the energy conversion efficiency and wave attenuation of PTO-integrated breakwaters. The optimal conversion efficiency (η_2) was calculated to be 80%. He et al. [93] created a Simulink model of OBWEC, and the load of OBWEC was the motor. According to the basic performance parameters of the generator and the electromagnetic theory, the power generation and power generation efficiency formulas of the model were derived. The results were verified with the AQWA simulation to prove the correctness of the model. Yan [94] studied the influence of the mass of the vibrating buoy on the energy capture of the OBWEC. It was found that the larger the mass of the buoy, the greater the momentum that could be captured, and then the wave energy could be absorbed to a large extent. The schematic diagram of "Berkeley Wedge" WEC breakwater [80], swing arm WEC [81], pile-restrained WEC [82], cone-shaped WEC [84], different bottom shapes floating WEC [86], vertical pile-restrained reversed L type [88] and rectangular heaving buoys WEC [90] are given in Figure 10.

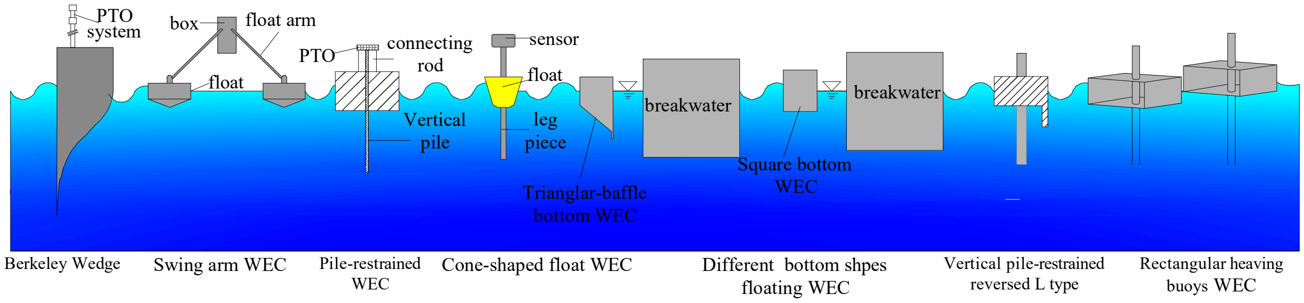


Figure 10. Different OFWECs [80–82,84,86,88,90].

The energy conversion of OFWEC is related to the relative translational motion of the float. The structure is simple and regular, and the contact area with the wave is not large.

Therefore, it is not dependent on wave characteristics, is easy to modularize and use in an array layout, and has a better economy [95]. From the research results, the results of numerical simulation were still high. The highest conversion efficiency obtained from the physical test was 82% ([80]). Unfortunately, the physical test did not carry out the power generation efficiency test.

2.3.2. Oscillating Pendulum WEC (OPWEC)

In this paper, the oscillator performs a pitching motion called oscillating pendulum WEC (OPWEC). The system is composed of three parts, which are the swing plate part (blade or pendulum, etc.), the hydraulic cylinder part, and the support/frame part. The swing plate (blade or pendulum, etc.) is connected to the support (or bracket). After the swing plate is subjected to the impact and buoyancy of the wave, it swings or rotates back and forth around the rotating shaft and then drives the hydraulic cylinder to move back and forth. The wave energy is converted into the hydraulic energy of the hydraulic cylinder, and then the hydraulic energy is transmitted to the generator. The hydraulic energy is converted into electrical energy, and the wave energy generation process is completed through secondary energy conversion.

OPWEC started to be used relatively late. In 1992, Stephen Salter invented the Swing Mace [15]. The converter mainly includes an axisymmetric column float. Under the action of waves, the float rotates around the bottom universal joint, thus driving the PTO system to generate electricity. In 2001, British Cameron et al. proposed the Oyster buoyancy pendulum converter and carried out sea trials in 2009. At present, the second-generation Oyster has been developed. In 2003, Finland's AW energy company developed the Wave Roller [21], which was completely immersed in the seabed. The converter was successfully tested in different sizes from 2003 to 2012. Aalborg University in Denmark and Langlee Wave Power AS in Norway jointly developed "Langlee WEC" in 2005 [23]. In 2009, Bio Wave was jointly developed by Australia's Bio Power Systems and Germany's Siemens. The commercial prototype was designed with a 1 MW water depth of 40–45 m, and the test of integration into the power grid was completed in August 2011. By the end of 2013, Bio Wave was commercially deployed on the South Coast of Australia.

In terms of physical experimental research, Li et al. [96] tested the oscillating blade WEC at a wavelength of 1.5 m, a period of 2 s, a wave height of 0.16 m, and a load resistance of 5 Ω. The output power of the generator was as periodic as the wave. The maximum instantaneous power was 2.83 W, the average output power was 0.48 W, and the average wave energy generation efficiency (η) was 4.37%. The generation efficiency was low, which may be applicable to small ships, but it was difficult to obtain large-scale power. Song et al. [97] studied the OPWEC of double-stroke hydraulic transmission through Matlab/Simulink simulation and model test. The results of the simulation and test were in good agreement, but the maximum output power of the test reached 75% of the simulation (H = 0.2 m), and the maximum output power of the test was about 0.01 kW. An eccentric OPWEC was designed by Shi et al. [98]. Physical experiments were carried out under different wave periods (T was 1.4–2 s), wave heights (H was 0.16–0.20 m), pendulum counterweights (5.0, 7.5, 10.0 kg), and mechanical loads (1–5 Nm). When the pendulum mass was 7.5 kg and the load was 3.5 Nm, the average power generation efficiency (η) was 7%.

In terms of numerical/theoretical research, Wang et al. [99] numerically studied the influence of hinge stiffness, hinge damping, and draft depth on the total power of the Pelamis WEC. The results showed that the relative rotation angle at the hinge between the cylinders was the main dynamic factor for generating power. The hinge stiffness and hinge damping had a great influence on the total power generated by the whole converter. Appropriately increasing the draft can obtain a larger total power. Yu et al. (2018) [100] proposed a buoy with an inertial pendulum OPWEC, which was simulated by AQWA. When the wave direction angle was 0°, the swing angle of the wave power generation system was large and stable, and the maximum swing angle was 17.8~16°.

However, its power generation and wave energy conversion efficiency have not been studied. Wang et al. [101] studied the wave energy use of the power generation converter with inertial pendulums. When the load damping coefficient was 0.006 Nms/rad, the maximum captured energy efficiency (η_1) reached 32.1%. Fan et al. [1] took OPWEC as the research object and used AQWA to analyze the influence of the net buoyancy, damping coefficient, and hinge position of the rotating joint of the buoyant pendulum on the energy capture characteristics of the buoyant pendulum wave energy generation device. When the optimal damping coefficient was 4.327×10^5, the average absorption power of the buoyancy to the wave energy was 3.99 kW, and the captured energy efficiency (η_1) was 20.58%. Yao et al. [102] established the linear power generation module model of the buoyancy pendulum-driven linear power generation system. By changing the spring stiffness parameters of the linear power generation module, the natural frequency of the linear power generation module was close to the wave frequency, and higher power generation efficiency could be obtained. Jamrud et al. [103] numerically simulated OPWEC (WEPG-PS). They concluded that the system had a power of 7.5 kW at ω = 300 rad/s and an induction generator of 50 Hz. Based on the concept of mechanical rectifier (MMR), Dai [70] proposed a two-stroke reciprocating OPWEC. Using Matlab and ADAMS simulation, they obtained that the peak generating efficiency (η) of MMR-PTO was 81.39%, while the peak conversion efficiency of hydraulic PTO was 47.56%. The two-stroke reciprocating pendulum could improve the wave energy conversion power of PTO. Fan et al. [104] solved the Cummins equation by establishing a Matlab/Simulink simulation model and calculated the maximum average power generation power of the hydraulic power system to be 84.15 kW (corresponding to the piston area of 0.1 m^2). We can see the schematic diagram of the swing mace [15], oscillating blade WEC [97], spherical pendulum WEC [100], inertial pendulum buoy WEC [101], OPWEC [1], and double-stroke reciprocating deflector WEC [70] in Figure 11.

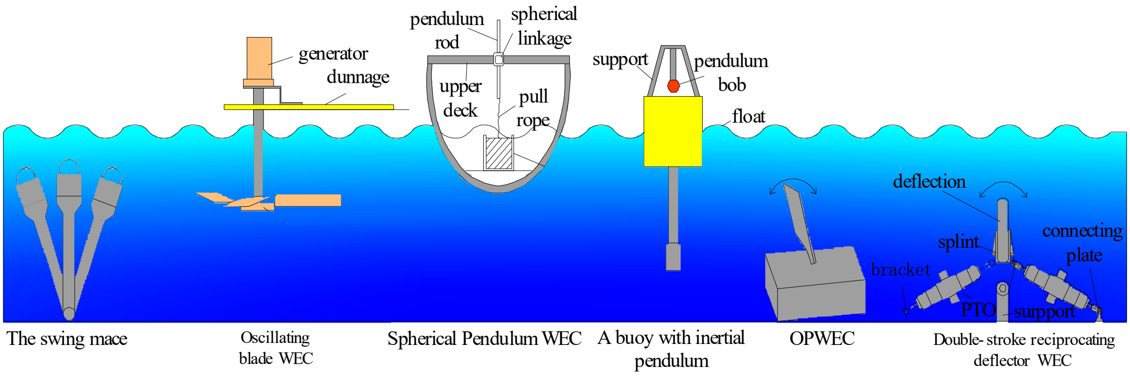


Figure 11. Different OPWECs [1,15,70,97,100,101].

Compared with other types of devices, OPWEC has a wider frequency response range and lower cost. However, from the current physical test results, the maximum energy conversion efficiency was 7%, and the maximum average power was 0.48 kW, which is relatively low.

2.3.3. Other Types of WEC (OTWEC)

In addition to the above common types, there is also a converter that combines OFWEC and OPWEC. The floating body system of a wave energy power generation device proposed by Qu et al. [105,106] consists of a main frame and four collection systems. The main frame consists of a peripheral frame, a pontoon and two sets of upper and lower fans. The collection system consists of a pendulum plate, a floating body and a floating body frame. The whole device floats at the sea level, and at the same time, it is connected to the seabed heavy object through the anchor chain and the other end is connected to the bottom end of the main frame. The authors used AQWA to simulate the energy capture effect of the independent heave motion of the pontoon and the independent pendulum wave of the pendulum plate, respectively. The captured energy efficiency (η_1) of the pontoon boxes was 42.8%, while the captured energy efficiency (η_1) of the pendulum plates was 14.8%, but there was no analysis of the simultaneous movement of the pontoon boxes and the pendulum plates.

There are also raft-type WEC, flexible capsule WEC, sea mushroom WEC, and so on. For example, Zheng et al. [107] proposed an elliptical cross-section raft WEC and numerically analyzed the power generation of the double-raft and three-raft devices. The difference between the two was little, and the power generation can reach 40 kW. Fang et al. [108] designed a multi-stage floating mechanical energy generation converter and a rectifier voltage regulator circuit. The converter was composed of a multi-cylinder buoy, variable direction acceleration mechanism, generator, rectifier, and voltage regulator circuit. The experimental results show that the power generation efficiency (η) of the power generation converter could reach 45.8%. However, the calculated power generation power includes the internal friction power of the circuit. For the power generation power alone, the power generation efficiency (η) was 14.73%. The power generation efficiency of this paper did not include the internal friction of the circuit, so it was based on 14.73%. Yang et al. [10] designed a flexible capsule-type WEC, which consisted of a strong shrinkage silicone tube, a water delivery vertical tube (opening above the vertical tube), and a power generation device. The silicone pipe was laid on the foundation bed to shrink and expand with the wave; the formation of pulsating water transport made the water level in the vertical pipe rise and fall with the pulsation, and the air was changed by expulsion and inhalation. The highest captured energy efficiency (η_1) of the air chamber was 63.4%. Yuan [75] numerically simulated the sea mushroom WEC. The WEC included an absorbing cylinder and an absorbing ring float. The absorbing cylinder was hinged on the seabed and performed pitch motion. The absorbing ring float was sleeved outside the absorbing cylinder and performed a heave motion relative to the cylinder. The maximum power generation of this sea mushroom type was simulated to be about 35 kW (the set scale was 1:15, and the model power generation was about 2.68 W), and generation efficiency (η) was 30%. Chen et al. [109] found the stable power of the trapezoidal and rectangular floating raft WEC to be 70–80 W. Chen et al. [110] proposed an integrated converter of square box floating breakwater with wave attenuation channel and oscillating buoy WECs. Fluent software was used to analyze the effects of different damping and channel configuration parameters on the wave attenuation and energy capture efficiency of the system. The results showed that the inlet of the wave attenuation channel was completely submerged, and the energy capture efficiency and wave attenuation effect were better. The captured energy efficiency (η_1) was 17.85%.

In recent years, there have been many studies on OBWEC, both in physical experiments and numerical simulations. OBWEC is considered to be one of the most economical converters, and it can be applied to deep-sea areas [9]. According to the results of physical tests, the highest power generation efficiency was 14.73% (reference [108]).

3. Analysis and Summary

3.1. Analysis

In this paper, the installed capacity of the engineering example and the power generation and each stage energy generation efficiency of the references are summarized and compared, as shown in Table 1 and Figure 12. In Figure 12, red, yellow, green, blue, and purple express OWEC, OWCWEC, OFWEC, OPWEC, and OTWEC, respectively. For Figure 12a, the data font representing the results of the physical test is depicted in black, while the red color signifies the numerical or theoretical calculation results. In Figure 12b,c, the data box is distinguished by three different colors: red, blue, and green, indicating respectively the wave energy conversion efficiency of the first, second, and third stages.

Table 1. Comparison of parameters of several converters.

Name	Location	Category	Capacity (kW)	Date
IPS buoy [3]	Sweden	OWCWEC	17	1980, 1981
N2 buoy [3]	Norway	OWCWEC	-	1981, 1982
Swedish hose-pump [3]	Sweden	OBWEC	30	1983–1984
Kaiyo [3]	Japan	OBWEC	1, 5, 10	1984
Kaimei [3]	Japan	OWCWEC	185	1985
TAPCHAN [12]	Norway	OWEC	350	1986
BBDB [3]	Japan	OWCWEC	5	1996
Might Whale [3]	Japan	OWCWEC	120	1998
Pico [14]	Portugal	OWCWEC	400	2000
LIMPET [32]	UK	OWCWEC	500	2001
Mutuku [49]	Spain Norway	OWCWEC	300	2001
Wave Dragon [3]	Denmark	OWEC	20	2003
Lyselil [3]	Sweden	OBWEC	10	2006
Pelamis [4]	UK	OBWEC	750	2007
SSG [37]	Norway	OWEC	350	2008
Biowave [111]	Australia	OBWEC	250	2008
Wave Rider [32]	Australia	OBWEC	1000	2011
DEXA [37]	Denmark	OBWEC	160	2011
Oyster [32]	UK	OBWEC	800	2012
StingRay [32]	America	OBWEC	500	2019
AWS [26]	Netherlands	OBWEC	10	2022
Wan Shan [5]	China	-	120	2015
Zhoushan [32]	China	OBWEC	500	2020

Note: “-”represents no relevant information.

Based on Table 1, most of the WEC projects are constructed using OWCWEC and are basically withdrawn from the construction of OWEC. Single project installation power is not more than 1000 kW; even those that are more than 500 kW are very few. It has been reported that many famous projects have been damaged or abandoned due to wind and waves, etc. [3]. Overall, the WEC project is still in the exploratory stage, and there is still a long way to go before a large-scale application. The academic research on the energy output of the wave energy converter accounts for a relatively small proportion, and there is less research on power generation efficiency. It focuses more on the structural force and motion characteristics of the converter. It can be seen from Figure 11 that there is no reference for calculating η by numerical simulation. The research on OBWEC, especially OFWEC, is more extensive. The results of physical tests and numerical simulations are quite different. Based on the results of the physical test power generation, the main research objects are OWEC and OPWEC, and OPWEC performs better than OWEC. Based on the results of the CWR of the physical test, OFWEC is better than OWEC or OWCWEC, and the maximum can increase to 82%. From the η under physical test, there is no relevant research on OFWEC. The highest power generation efficiency is in reference [58], with a η of 21.33%, which belongs to OTWEC. Comparing the results of the numerical simulation of power generation, OPWEC is better, with the maximum obtained in reference [104], which is up to 84.15 kW. In the study CWR results of numerical simulation, OFWEC performed better, and the maximum was 93.34% in reference [79]. In the research on energy output, most of the references focus on CWR (first or secondary energy conversion efficiency), and there are few studies on power generation efficiency. Overall, OBWEC performs better.

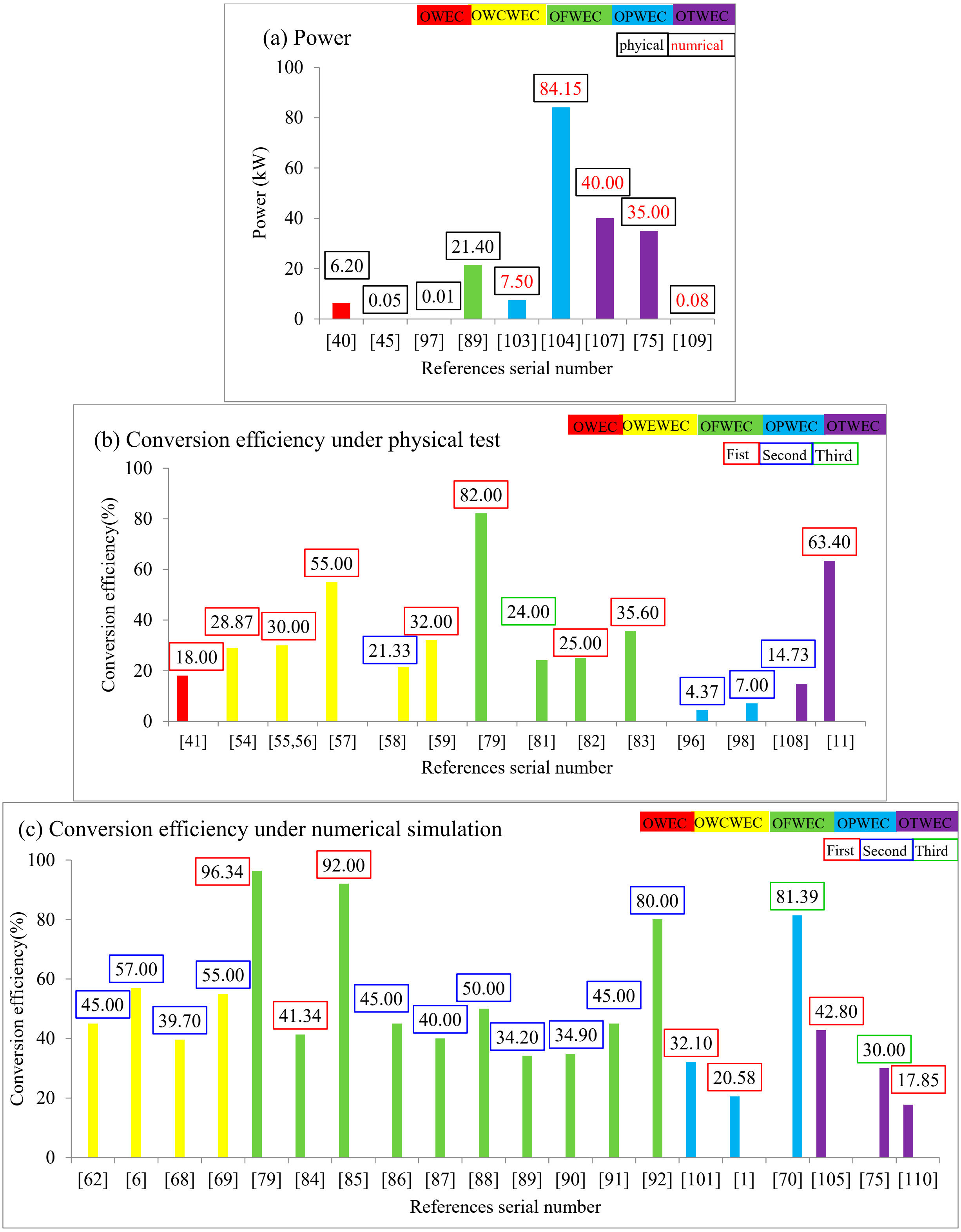


Figure 12. Power and conversion efficiency of the WECs in the references: (**a**) P of WECs [40,45,75,89,97,103,104,107,109], (**b**) conversion efficiency of WECs under physical test [11,41,54–59,79,81–83,96,98,108], and (**c**) conversion efficiency of WECs under numerical simulation [1,6,62,68–70,75,79,84–92,101,105,110]. Note: Except for the maximum values in references [45,76,89], the other values are the average power generation (the approximate words such as 'stable' and 'maintenance' in the reference are regarded as average).

3.2. Problems and Disadvantages

Based on the above, the current research on wave energy converters has the following deficiencies.

(1) Fewer studies on physical experiments

From Figure 12, it can be seen that the researchers' enthusiasm for logarithmic simulation is greater than that of physical experiments. Although numerical simulation can obtain results conveniently, quickly, and economically, the physical experiment is particularly important for the true effect of the converter and the verification of logarithmic simulation. Therefore, it is recommended to increase the proportion of investment in physical experiments.

(2) Fewer studies on power generation efficiency

It can be seen from the previous article that WEC needs to undergo two or three stages of energy conversion to complete the conversion of wave energy to electric energy. Most of the current research focus on the first or second-stage energy conversion efficiency, and the ultimate goal of WEC is electric energy. More in-depth research on power generation efficiency should be carried out.

(3) Lower generating efficiency

Lower power generation efficiency is the most important issue. A large number of studies have been devoted to obtaining efficient wave energy conversion converters. However, the current power generation efficiency is basically less than 30%, and it is extremely urgent to improve the power generation efficiency of the converters.

(4) Lower engineering applicability

Although there have been thousands of types of converters studied at present, few of them are really suitable for engineering applications. Increasing the practical research of the converter can be better put into engineering, put into operation, and increase social benefits.

(5) Greater influence on sea ecological environment

As the world pays more and more attention to the safety of the marine environment, the wave energy converter must consider the impact on the environment. This is not only whether it causes chemical pollution to the marine environment but also whether it affects seawater quality exchange, marine biological habitat, and so on. Although most of the current research converter captures energy by float movement and does not block seawater, it affects seawater exchange to a certain extent.

(6) Greater wave force subjected

As mentioned above, many researchers have focused on the structural force of the converter. It is a very important problem that the structure is subjected to big wave force, especially a larger horizontal force. However, the current structural force research is mostly to optimize the structure so that the structure can resist the wave force, and little attention has been paid to the structure with small horizontal force, such as the wave heaving plate WEC.

(7) Less information about current WEC engineering

Including this article, there has been less attention paid to international WEC engineering in recent years, and there are few reports on engineering applications. Increasing international attention has a positive effect on improving research.

(8) High cost

At present, the cost of WEC is much higher than that of conventional power generation, which hinders the marketization process of WEC. In order to popularize and scale up wave power generation, the cost of power generation must be reduced. How to reduce costs is a hot topic that needs in-depth analysis.

(9) Lack of standards and norms

Compared with other mature power generation methods, WEC lacks relevant policies and regulations. There are few national standards and industry standards involving wave energy converters. There is no basic standard comparison for the design scheme of wave energy converters. Various tests, such as structural strength tests, fatigue tests, generator-type tests, material corrosion resistance tests, and so on, also lack corresponding test standards, which become an important factor hindering the industrialization development of wave energy power generation.

3.3. Prospect

Zheng et al. [112] calculated the global ocean wave energy resource storage. Tables 2 and 3 summarize the global energy flux density and effective storage distribution according to [112]. Based on the "Division of Marine Energy Resources in Rural Coastal Areas of China", the average theoretical total power of wave energy resources along the coast of China is 12.84 GW [113]. Table 3 and Figure 13 summarize the power density distribution and proportion of wave energy storage capacity in coastal provinces in China. As can be seen from Tables 2 and 3 and Figure 13, the global ocean energy is huge, and the China Sea does not belong to the dominant area of global wave energy resources, but there are still relatively rich areas. Therefore, the development of wave power generation is promising.

Table 2. Global wave energy flux density and effective storage distribution.

Region	Energy Flux Density kW/m	Region	Effective Storage Energy 10^4 kW/(h·m)
South Indian Ocean, south of Australia	60–100	Westerlies of the Southern Hemisphere	50
North Pacific westerlies, North Atlantic westerlies	30–50	Westerlies in the Northern Hemisphere	30–50
Mid-low latitudes of the Atlantic Ocean	10–20	Middle and low latitudes	5–30
The northern Indian Ocean, the East China Sea and the northern South China Sea	10		

Note: Data from Zheng, reference [112].

Table 3. Wave power density distribution in China [113].

District	Power Density (kW/m)
Bohai Strait	7.73
The north and south ends of Taiwan	6.21–6.36
Central Zhejiang	6.29
Haitan Island, Fujian	5.32–5.51
Xisha region coast	4.05
Southern and northern Zhejiang	2.76–2.82
Eastern Guangdong	3.62
South of Haitan Island, Fujian	2.25–2.48
The southern coast of Shandong Peninsula	2.23

Note: Data from Zheng, reference [112].

As a renewable energy technology, wave power generation will certainly promote the adjustment and optimization of energy structure, reduce carbon emissions and environmental pollution, and bring good economic and social benefits. In the process of the application and promotion of wave energy power generation, it is necessary to strengthen technology research and development and industry cultivation and constantly improve technology maturity and market competitiveness. This article inevitably has improper and negligent sections, and we hope that readers will correct them.

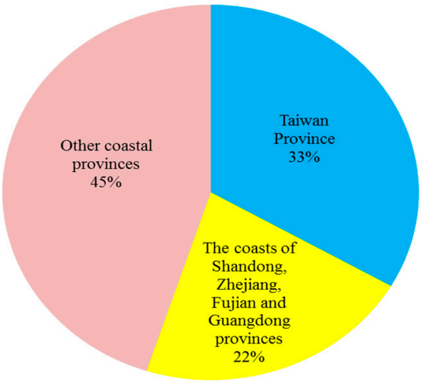


Figure 13. Proportion of wave energy storage capacity in coastal provinces and cities of China (Data from reference [113]).

4. Conclusions

By summarizing the research on wave energy generation converters, the following points are concluded:

(1) It can be seen that the comprehensive performance of OBWEC is better, and the power generation efficiency under the test condition reached 21.33%.
(2) The numerical simulation or theoretical research on wave energy power generation devices is relatively important, and it is hoped to conduct more physical experiment research.
(3) There are many studies on primary or secondary efficiency conversion of WECs, and it is suggested to increase the research on power generation efficiency.
(4) It is hoped that wave energy discovery devices will continue to be developed with higher power generation efficiency and less wave load.

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Conflicts of Interest: The authors declare no conflicts of interest.

Nomenclature

T	Period of the wave, s
h	depth of water, m
H	height of the wave, m
L	length of the wave, m
ω	wave angular frequency, rad/s
γ	JONSWAP spectral shape factor
η_1	captured energy efficiency, %
η_2	second stage conversion efficiency, %
η	third stage (generating efficiency), %

Abbreviations

WEC	wave energy converter
OWEC	overtopping WEC
OWCWEC	oscillating water column WEC
OBWEC	oscillating body WEC
OFWEC	oscillating float type WEC
OPWEC	oscillating pendulum wave WEC
OTWEC	other type of OBWEC
PTO	power take-off

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