Journal of
Marine Science and Engineering

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Review

Wave Energy Conversion through Oscillating Water Columns: A Review

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Abstract: An oscillating water column (OWC) is designed for the extraction and conversion of wave energy into usable electrical power, rather than being a standalone renewable energy source. This review paper presents a comprehensive analysis of the mathematical modeling approaches employed in OWC systems, aiming to provide an in-depth understanding of the underlying principles and challenges associated with this innovative technology. A prominent classification within the realm of wave energy devices comprises OWC systems, which exhibit either fixed or floating configurations. OWC devices constitute a significant proportion of the wave energy converter prototypes currently operational offshore. Within an OWC system, a hollow structure, either permanently fixed or floating, extends below the water's surface, creating an enclosed chamber where air is captured over the submerged inner free surface. This comprehensive study offers a thorough assessment of OWC technology in conjunction with air turbines. Additionally, the investigation delves into theoretical, computational, and experimental modeling techniques employed for analyzing OWC converters. Moreover, this review scrutinizes theoretical, computational, and experimental modeling methodologies, providing a holistic understanding of OWC converters. Ultimately, this work contributes a thorough assessment of OWC technology's current state, accentuating its potential for efficient wave energy extraction and suggesting future research avenues.

Keywords: wave energy; oscillating water column device; wave power extraction; marine renewable energy; hydrodynamics of OWC

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Citation: Gayathri, R.; Chang, J.-Y.; Tsai, C.-C.; Hsu, T.-W. Wave Energy Conversion through Oscillating Water Columns: A Review. *J. Mar. Sci. Eng.* **2024**, *12*, 342. https://doi.org/10.3390/jmse12020342

Academic Editors: Jose Santos Lopez Gutierrez, Carlos Guedes Soares, Rafael J. Bergillos, João Miguel Dias, Markes E. Johnson, Naomasa Oshiro and Alvise Benetazzo

Received: 13 November 2023
Revised: 9 February 2024
Accepted: 12 February 2024
Published: 17 February 2024

1. Introduction

In recent decades, there has been a growing interest in renewable energy sources due to concerns related to environmental pollution, rising costs, and the depletion of fossil fuels. Ocean wave energy has gained significant attention as a promising alternative. Researchers worldwide are actively working on making it a cost-effective energy source. Among the various ocean WEC designs proposed, the OWC concept stands out for its simplicity and versatility. Ocean waves represent a clean energy source that holds promise in addressing our global energy needs as we strive for a more sustainable future. One of its notable advantages lies in the predictability of energy generation, which helps stabilize electrical grids, setting it apart from the less reliable solar and wind energy sources. The potential to harness wave energy for practical use has motivated countless innovators throughout history. By 1980, over a thousand patents had already been recorded, and this number has continued to rise significantly. In 1799, [1], a French inventor successfully obtained the initial patent for a wave-driven apparatus engineered to propel sawmill machinery.

Numerous comprehensive reviews on the topic of wave energy conversion have been disseminated through various mediums, encompassing books, conference and journal publications, as well as reports. Notably, a seminal book in 1981 [2] is a pioneering work in this field. Additionally, significant contributions are found in the works authored by [1,3–6]. Valuable insights into contemporary advancements in the field are also available in a report commissioned by the UK Department of Energy in 1999 [7], as well as the conclusive 2003 report by the European Thematic Network on Wave Energy [8], supported by the European Commission. Concise reviews can be found in [9–13]. Since studies on wave energy have been conducted in Japan since the 1940s, Yoshio Masuda is recognized as the inventor of the field. He devised a wave energy-powered navigation buoy equipped with an air turbine, later referred to as a floating OWC. From 1965 onward—and subsequently, in the United States—these buoys have been commercially available in Japan as documented by [14]. Subsequently, in Japan, Masuda advocated for the building of a considerably bigger device, the Kaimei (80 m $\times$ 12 m). This structure functioned as a floating testing platform for multiple OWCs equipped with a diverse range of air turbines [15].

In 1974, the research conducted by [16] drew the focus of the global scientific community toward wave energy. In 1975, the British government launched an ambitious wave energy research and development effort [17], which was swiftly followed by the Norwegian government. Two full-sized shoreline prototypes (rated power of 350 and 500 kW) were constructed in Bergen, Norway, in 1985. A small (75 kW) OWC shoreline prototype that was built on the Scottish island of Islay in 1991 appears to have been the most successful of the activities that took place in Europe in the years that followed, up to the early 1990s [18]. Around the same period, two prototypes of OWC developed in Asia: one was a 60 kW converter located in the port of Sakata, Japan [19], and the other was a bottom-mounted 125 kW facility in India [20]. A hydrodynamic process with significant theoretical complexity called wave energy absorption involves highly intricate diffraction and radiation wave processes. This explains why some prominent applied mathematicians played crucial roles in wave energy research published in the second half of the 1970s, much of which concentrated on theoretical hydrodynamics. The Implementing Agreement on Ocean Energy Systems (IEA-OES), which comprises 17 nations as contractual parties, was initiated in 2001 by the International Energy Agency. Its primary objective is to foster and promote international collaboration and the exchange of information in the areas of ocean energy research, development, and demonstration. The 2008 Annual Report from IEA-OES provides a summary of the current worldwide wave energy activity. Further, a hydrodynamic process with significant theoretical complexity called wave energy absorption involves highly intricate diffraction and radiation wave processes [21]. This shows that theoretical hydrodynamics constituted a major part of the wave energy research published during the second half of the 1970s, with some prominent applied mathematicians playing vital roles. According to the IEA-OES, there are now more than one hundred wave energy conversion systems being developed throughout the world. These systems are designed to collect energy from tides and currents along coasts, utilize temperature and salinity gradients across different water depths, and capture energy from wind waves and oceanic gravity. While wave energy extraction technologies have become increasingly efficient in recent decades, sustainability and cost-effectiveness are still major hurdles to their widespread use. By the year 2040, as the global population surpasses 9 billion, it is projected that worldwide energy consumption will increase by nearly 30% compared to the levels observed in 2010 [22]. Concurrently, there is a substantial growth in wave energy in the US and Canada, including research institutes, national and regional administrations, and industries, resulting in a slew of ocean energy events and conferences [21]. Although there are many different designs and ideas, WECs may be divided into three basic groups: (i) point absorbers, (ii) terminators, and (iii) attenuators. Within these categories, there are further distinctions based on their operational methods, such as oscillating water columns, immersed pressure differential devices, oscillating wave surge converters, and overtopping devices. The oscillating water column, which was initially introduced in the early 19th century, has been a prominent wave energy conversion device and is still considered state-of-the-art [23].

Generally, near- and off-shore WEC devices are designed based on the principles of oscillating water columns, wave overtopping, wave absorption, and submerged oscillations. However, the reliability and cost-effectiveness of these systems are highly sensitive to environmental conditions, and detailed mathematical models and efficient mathematical techniques need to be developed to design WECs optimally. Among the many WEC devices, OWC devices are currently one of the leading innovative technologies in development for wave energy extraction. OWC systems offer superior management of energy conversion efficiency and peak-to-average power when compared to other technologies. This advantage arises from the foreknowledge of wave patterns and periods, as well as the effects of climate and geography. Due to its few moving parts, especially in water, OWCs also demonstrate flexibility to various shoreline designs, assuring dependability and inexpensive maintenance. The substantial demand for renewable wave energy extraction has spurred numerous mathematical and experimental investigations on shore-connected OWCs ([24–26], etc.). However, there is a considerable need for the optimization of sustainability and costs of OWC implementation for large-scale implementation of the device.

Accordingly, integrating WECs with marine structures like breakwaters, docks, and piers, or with shoreline segments, can enhance their economic models and increase their viability. These structures offer financial benefits related to the construction, configuration, and restoration of the shoreline. Moreover, these structures can be integrated with mechanical power take-off systems (PTOS) that are used in small-scale wave energy converters because of their high energy transfer efficiency. Therefore, a hybrid model that incorporates a power take-off system into floating and submerged structures has the potential to provide both coastline defense and commercialized wave energy extraction [27–29]. On the other hand, in recent decades, floating constructions have been extensively used in ocean engineering, while flexible, porous structures are also being implemented as cost-effective coastal protection systems [30–32].

[23,33] include more detailed evaluations of OWCs in addition to reviews on WECs in general [13,21]. An in-depth history of wave energy conversion development, in general, and OWCs, in particular, up to around 1995, may be found in a book written by a freelance writer, from a non-technical perspective; see [1]. There is limited availability of information specifically on OWC control, despite the availability of reviews, comparative studies, and books on control systems for general wave energy installations. The paper will provide an overview of offshore OWC systems as they are considered the most promising among WECs for constructing both high and low-power plants while maintaining minimal environmental impact. The assertion made in our paper regarding offshore OWC systems being considered the most promising among WECs is substantiated by the statement from [34]. In their work, [34] acknowledged that among the various wave energy conversion concepts, OWC is recognized for being extensively investigated and well-developed. Different studies have identified challenges resulting from the volatility of the properties of ocean waves and the sustainability of energy converters of the waves in a severe ocean environment [35,36]. The review by [36] provides a comprehensive overview of the types of WECs, their operational principles, and the design challenges they face, particularly focusing on the environmental sustainability of these systems. Building upon this, our study emphasizes the suitability of OWC systems for both high and low-power plants while maintaining a minimal environmental impact. Additionally, it delves into practical and theoretical approaches for converting wave motion into electrical power. The paper is structured as follows: Section 2 presents the major review analysis of OWC technology. Sections 3 and 4 are devoted to the types of OWC and mooring systems, whereas the conclusions are made in Section 5.

2. OWC Technology

Yoshio Masuda (1925–2009), a Japanese navy officer who carried out research in Japan in the latter half of the 1940s, is largely regarded as the father of modern wave energy technology. He designed a (floating) OWC, an air turbine-equipped navigation buoy powered by wave energy. Initially, buoys similar to those that have been widely distributed in Japan since 1965 were the first wave energy devices to be successfully released into the ocean (and, subsequently, in the USA). Traditional unidirectional air turbines were incorporated into Masuda's navigation buoys, necessitating a set of rectifying valves (Figure 1). The whistling buoy utilized as a navigational aid is the first instance of an OWC. It was viewed as the conventional bell buoy replacement in the nineteenth century (as a sensory warning tool). A whistling buoy of this type was patented by J. M. Courtney of New York (Figure 2), and was said to be in use throughout the US coast in 1885, according to a report in *Scientific American*.

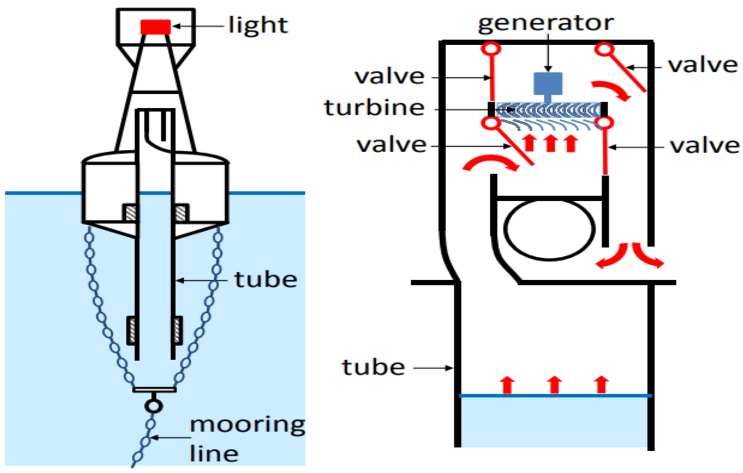


Figure 1. Layout of Masuda's navigation buoy ([37] 2006). The airflow via the rectifying and turbine valves is shown in detail on the right.

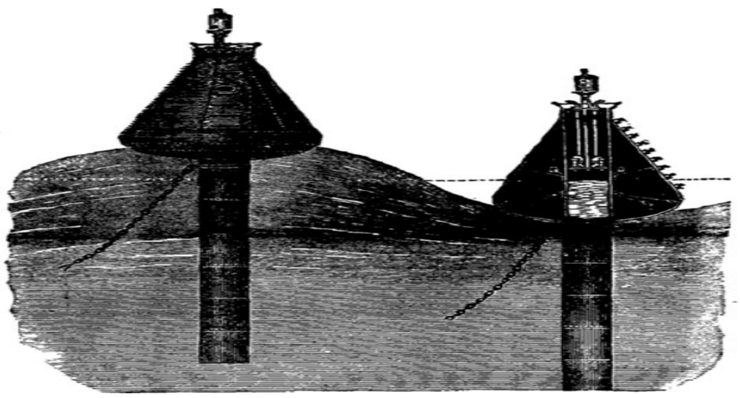


Figure 2. Courtney's whistling buoy ([23] 2012).

Since 1989, fifteen OWC plants have been constructed. While some have stopped operating, others are still in use. The first OWC ever constructed was a wave power buoy in the Sea of Japan, constructed in 1983. This OWC plant generated 40 kW of rated electricity using a Wells air turbine power generator. In 1985, the full-sized OWC was installed in Toftestallen, close to Bergen, as part of the more modest Norwegian scheme. The plant used a vertical-axis Wells turbine and had a 500 kW nominal rating. Although the functioning of the plant was not formally reported, it was well known that it was less than anticipated. Due to the steel structure's bolted attachment to the concrete base failing, the facility collapsed in a storm in 1988. A modest (75 kW) OWC shoreline prototype, equipped with a Wells turbine and installed on the Scottish island of Islay (commissioned in 1991; see Figure 3), was the most notable success of the subsequent years' activity in Europe, which continued until the early 1990s. In 1989, in Shanwei City, Guangdong province, China began constructing an OWC facility. The plant produced a rated power of up to 100 kW between 1989 and 1991 using an impulse turbine with a fixed waveguide, but it was damaged and could not be utilized after that. Beginning construction on a second OWC facility in 1990 in the Port of Sakata, Japan combined the converter system with the breakwater to produce a rated output of 60 kW using the Wells turbine technology. In the same year as the Port of Sakata facility, India established its first OWC plant, Trivandrum. Trivandrum's converter system achieved 125 kW of rated power by using a Wells turbine. The turbine was later converted to an impulse turbine by Trivandrum. In 1990, a manufacturing plant was constructed at Vizhinjam, India. The Wells turbine utilized in the first testing phase was swapped out in 1997 for an impulse turbine, which had a guiding vane connected to regulate the vanes' pitch automatically. The plant's rated power was 75 kW from April to November and 25 kW from December to March each year.

Figure 3. Oscillating water column on the island of Islay, Scotland, (courtesy of M. Folley).

As they continued to develop the technology, Japan unveiled their first Mighty Whale at Gokasho Bay in 1998. The facility produced up to 110 kW of electricity from its three-chambered OWC floating structure between 1998 and 2001 using a Wells turbine with guiding vanes. Australia developed the Energetech wave energy converter a year after the Mighty Whale was first introduced. With the installation of a variable pitch control Wells turbine, the fixed-structure device was able to attain a 500 kW rated output. The identical Wells turbine with guiding vanes that was previously constructed and utilized in the Mighty Whales was installed in a fixed-structured OWC on Pico Island in the Azores, Portugal, in 1999. Since then, a full-scale permanent structure OWC has allowed the plant to reach a rated output of up to 400 kW. It took a full 12 years to produce power before it was completely deactivated in 2010. Japan made further investments to establish an OWC facility at its port in Niigata. With a maximum recorded power of 800 W, the impulse turbine utilized in the plant achieved a rated power of 450 W. From June to September of 2007, the plant's four-month operational window was limited. In Galway, Ireland, a 1:4 scale model of a rotating backward bent duct buoy (BBDB) OWC with a CORES backward duct was constructed in 2008. It was driven by an impulse turbine equipped with stationary guiding vanes. It functioned until the year 2011 and reached a maximum rated output of 13 kW. Spain launched the Mutriku approach in 2011 and is still utilizing it now. Biplane Wells turbines, with an output of 296 kW, are used. On Scotland's Islay Island, the LIMPET facility was constructed in 2012 and has a contra-rotating Wells turbine. The plant produced 500 kW of electricity at first, but the next year it was reduced to 250 kW. This full-scale fixed-structure OWC was in operation from 2012 until 2018. In the Italian harbor of Civitavecchia, REWEC3 was first introduced in 2016. With a Wells turbine and a breakwater-integrated U-shaped OWC system, this still-in-operation plant generates 25 kW of rated electricity. On Yongsoo, Jeju Island, Korea's OWC plant, which was constructed in 2017, is undergoing a sea trial. It can produce up to 500 kW of power by using impulse turbines with static guiding vanes connected.

A turbine at the aperture of an OWC device uses the fluid's oscillation at the free surface—a result of repeated incident waves—to drive a volume of air in a single direction. Figure 4 illustrates the principles behind the wave energy conversion in an OWC system. The conversion process consists of two stages. The wave energy compresses the working fluid before the power take-off (PTO) activates, converting hydrodynamic contact into mechanical power. In the subsequent stage, the generator transforms mechanical energy into electrical energy. The OWC device also successfully serves as a pump, capturing wave energy by using the free-surface movement as a piston [23,38,39].

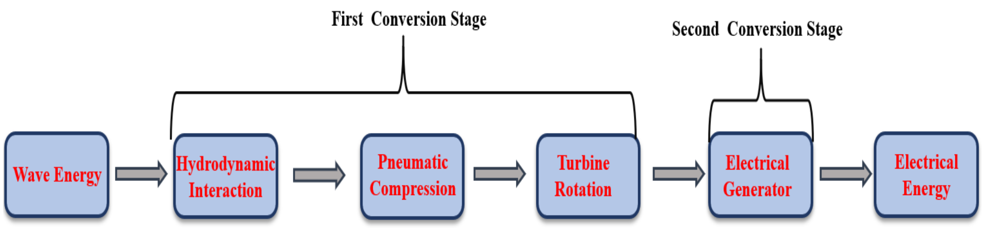


Figure 4. Working principle of OWC ([38] 2019).

The concept behind OWC involves harnessing wave surface motion to compress the air within a column. Bidirectional airflow and pressure fluctuations occur inside the cylinder as a result of the surface rising and falling in response to wave peaks and troughs. To enable continuous rotation in one direction despite the constantly changing airflow, these bidirectional airflow systems require a turbine capable of self-rectification. The most commonly used turbine in OWCs is the Wells turbine, which was created by Queens University professor Alan Arthur Wells [40]. By using symmetric airfoils, this turbine can spin in one direction regardless of the direction of the airflow, which helps it overcome the problem of variable airflow rates. Other turbine options have been suggested, including the Savonius turbine [41] and the self-rectifying bidirectional impulse turbine [42]. Current research in this area is focusing on potential improvements. One significant benefit of OWCs is their versatility in terms of deployment locations within the sea, depending on their structure and design:

- Incorporation into breakwaters along the shoreline: This is a widely adopted model that reduces deployment and maintenance costs.
- Nearshore deployment: They can be utilized in the form of multiple floating OWCs.
- Offshore utilization: They can be incorporated into buoys and floating constructions.

2.1. Fixed OWC Structure

Although many different approaches to energy extraction have resulted in the design of numerous systems, only a few full-scale prototypes have been constructed and placed in open coastal waters. These prototypes, which are frequently referred to as first-generation devices, are located along the coast or in nearshore areas. The benefit of using shoreline devices is that they do not require long underwater electrical lines or deep-water anchors, making installation and maintenance simpler. The natural concentration of wave energy from diffraction and/or refraction can partially offset the relatively less powerful wave conditions at the coastline (assuming the device is positioned effectively for this reason). The OWC device is built as an open, partially submerged concrete or steel structure below the water's surface, with trapped air above the free surface (see Figure 5). Incoming waves cause this internal free surface to oscillate, creating airflow via a turbine and driving an electrical generator. The axial-flow Wells turbine, developed in the mid-1970s, offers the advantage of not needing rectifying valves and has been employed in the majority of prototypes.

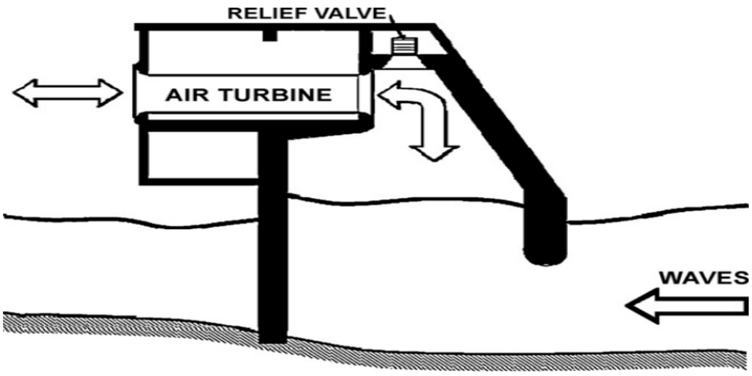


Figure 5. A view showing the cross-section of a bottom-standing OWC (Pico plant).

It has been established both theoretically [43] and experimentally (since the early 1980s) that extending the chamber structure with protruding walls, whether natural or man-made, in the direction of the waves, can significantly improve the process of absorbing wave energy. This results in the formation of a harbor or collector, a concept that has been incorporated into the design of most OWC prototypes. Additionally, Energetech, an Australian company, has created a technique for this use that makes use of a sizable parabolic-shaped collector, which resembles a Tapchan collector. This technology was attempted in 2005 in Port Kembla, Australia, for a nearshore prototype [44]. The primary innovation lies in the converging wall's size, which is far larger than the OWC's actual dimensions [45].

The most critical elements in OWC technology, significantly impacting the economic feasibility of wave energy production, involve the design and construction of the structure, excluding the air turbine. The integration of the plant structure within a breakwater offers several advantages: shared construction costs and significantly improved access for construction, operation, and maintenance of the wave energy facility. In 1990, Sakata, Japan's port saw a groundbreaking example of this integration in action [19], when one of the caissons that made up the breakwater was specifically built to serve as the OWC in addition to the mechanical and electrical apparatus. A few other examples of the concept of a 'breakwater OWC' have been implemented: the 0.75 MW twin-chamber OWC plant that is scheduled to be installed at the head of a breakwater at the mouth of the Douro River in northern Portugal [46] and the newly built breakwater at the port of Mutriku in northern Spain. The latter features 16 chambers and 16 Wells turbines, each rated at 18.5 kW [47]. Boccotti [48] suggested an alternative geometric method for an OWC incorporated into a breakwater, utilizing a quasi-two-dimensional terminator arrangement. In southern Italy, near the eastern shore of the Strait of Messina, a field experiment was carried out to validate this idea [49].

2.2. Floating OWC Structure

Yoshio Masuda led the invention of floating systems in Japan in the 1960s and 1970s, which were the first OWC converters to be deployed at sea. These comprised the large Kaimei barge and navigation buoys driven by waves. Masuda developed a new design for a floating OWC known as the backward bent duct buoy (BBDB) after realizing the shortcomings of the wave-to-pneumatic energy conversion in the Kaimei system. It was discovered that the BBDB design, which has the OWC duct orientated backward from the direction of the incident waves, had benefits over the forward-facing duct variant [50]. This configuration kept the floating structure's draft within reasonable bounds while enabling a long enough water column to reach resonance. Several nations, including Japan, China, Denmark, Korea, and Ireland, studied and tested the BBDB converter concept. In China and Japan, it was employed to supply power for around one thousand navigation buoys [51,52]. Ireland has been working on creating a large-scale BBDB converter that can be used in open waters for some time now. Since late 2006, tests have been conducted in the protected waters of Galway Bay in western Ireland using a 1/4th-scale model that is 12 m long and features a horizontal-axis Wells turbine [21].

The Japan Marine Science and Technology Center developed the Mighty Whale, another floating OWC converter, following theoretical studies and wave tank testing. A full-scale model with a floating structure of 50 m in length, 30 m in width, 12 m in draft, and 4400 tons in displacement was then developed and built. The structure incorporates three air chambers positioned at the front, arranged side by side, as well as buoyancy tanks [53]. A Wells air turbine attached to each of these air chambers powers an electric generator, yielding a total rated power output of 110 kW.

3. Hydrodynamics Of OWC

Due to the accessibility of wave patterns, period information, and awareness of geographical and climatic wave factors, regulating the effectiveness of energy conversion and peak-to-average power in OWC systems is easier than in other technologies. Additionally, OWCs are adaptable to various shoreline configurations, making them reliable and low maintenance, thanks to their limited moving parts, especially underwater. Theoretical studies play a crucial role in revealing hydrodynamic characteristics, primarily using linear water wave theory. The practicality and efficiency of the linearized approach have led to the continuous development of theoretical studies for OWC devices [54–60]. [24] investigated the behavior of the OWC device near an impermeable wall using the Galerkin technique (see Figure 6). Using the eigenfunction expansion method, [61] examined the radiation and diffraction problem for a circular OWC. Utilizing an eigenfunction expansion approach and a cylindrical coordinate system, [25] investigated the wave power extraction effectiveness of a floating, circular OWC device. [62] employed the eigenfunction expansion and boundary element method to investigate the impact of a single OWC device over a changing bottom topography (see Figure 7).

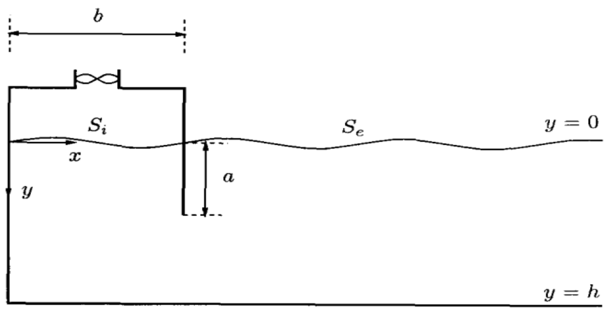
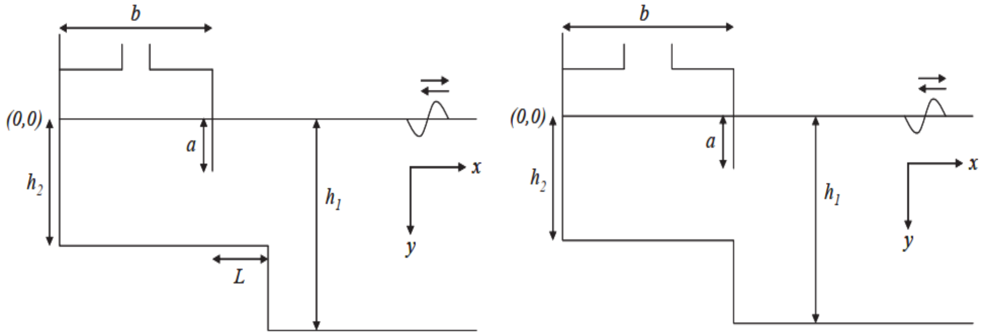
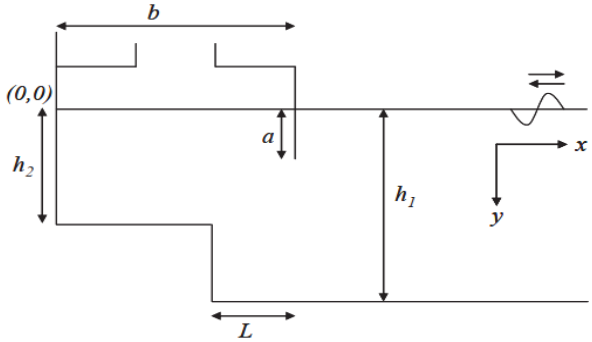


Figure 6. Oscillating water column ([24] 1995).

As we approached the twenty-first century, theoretical models became more developed and widely used to study the effectiveness of OWC devices with more geometrically complex features when subjected to more plausible external environments; the objective was to meet the demands of commercial usage as quickly as possible [26,63]. In a study on the linked hydro-electromechanical action of a two-dimensional piezoelectric device, [64] found that the device could absorb sufficient energy for low-power electronics, such as wireless networks, LEDs, computers, and sensors. [22] presented a review on floating WEC and a technique for mooring design.



(**a**) Step outside and below the water column



(**b**) Step inside the water column

Figure 7. Single oscillating water column ([62] 2013).

The roles of the turbine power take-off system (PTOS) and the surrounding environment in extracting wave power from an offshore breakwater-integrated Oscillating Water Column (OWC) have also been explored. A conventional OWC consists of a hollow pressurized chamber with an open undersea bottom and a PTOS on the chamber's roof. It is also found that by tuning the PTO dampers for maximum power, the extraction of wave power and attenuation of wave can be achieved. Further, the PTOS of WECs can be classified into the following (i) direct-driven PTOS, (ii) hydraulic PTOS, and (iii) mechanical PTOS [29]. A finite element analysis on the wave power absorption by an array of OWC was conducted by [65]. By using the CFD model, [27] studied the effects of PTO damping and the efficiency of an onshore OWC. The wave power dissipation by an array of floating/submerged permeable flexible plates was investigated using analytical techniques given by [66,67]. Assuming that the permeability of the flexible plates serves as a simpler mechanism for power take-off, the significant potential of elastic plates for wave energy extraction has been shown. Using vertical power take-off (PTO) mechanisms that connect a floating circular plate to the seabed, [28] presented a system for extracting wave energy. Most recently, [68] studied the effectiveness of a hybrid WEC device made up of a piezoelectric plate and an OWC device. Later, [69] investigated the extraction of wave power from a clam-type wave energy converter. Additionally, the performance of an OWC device and a piezoelectric plate placed on an undulating seabed were examined by [68] using the boundary element approach and taking into account the Bretschneider spectrum for irregular incident waves (See Figure 8).

In addition, multi-chamber OWCs are anticipated to be constructed to fully harness the local wave power and produce large quantities of energy [70,71]. A hypothesis was developed by [72] to estimate the efficacy of multiple OWCs in a given depth reflecting wall. They used the simple technique of the matched asymptotic expansions approach to construct the approximation theory. A thorough experimental investigation on the power absorption effectiveness of an array of multi-resonant OWC wave energy caissons was conducted by [73]. [74] conducted a theoretical analysis of wave energy absorption caused by multiple OWCs. By employing the finite element method, [65] investigated the effectiveness of a multi-chamber OWC. They noticed that even at great distances, nearby OWCs had a significant influence on the power collection efficiency of individual devices. According to research conducted by [75], the efficiency of the device may be significantly increased across a broad frequency range by placing a dual OWC chamber on a sloping sea bottom (Figure 9).

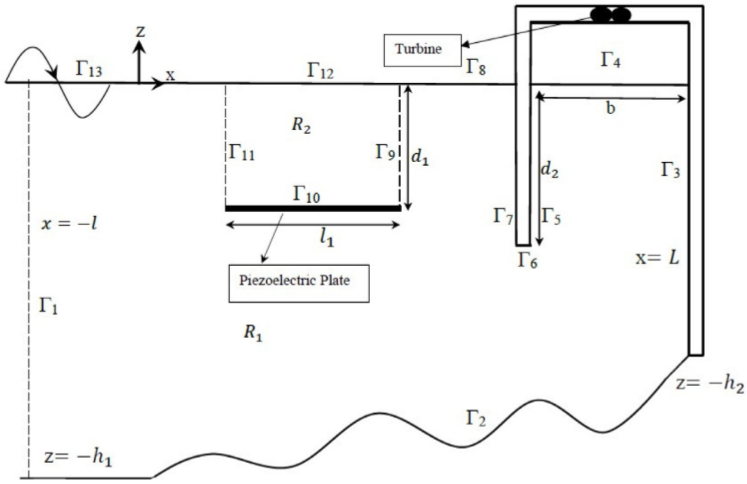


Figure 8. Piezoelectric plate and the OWC device placed over an undulated seabed ([68] 2023).

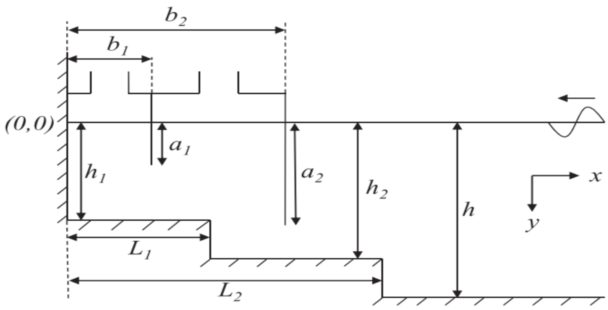
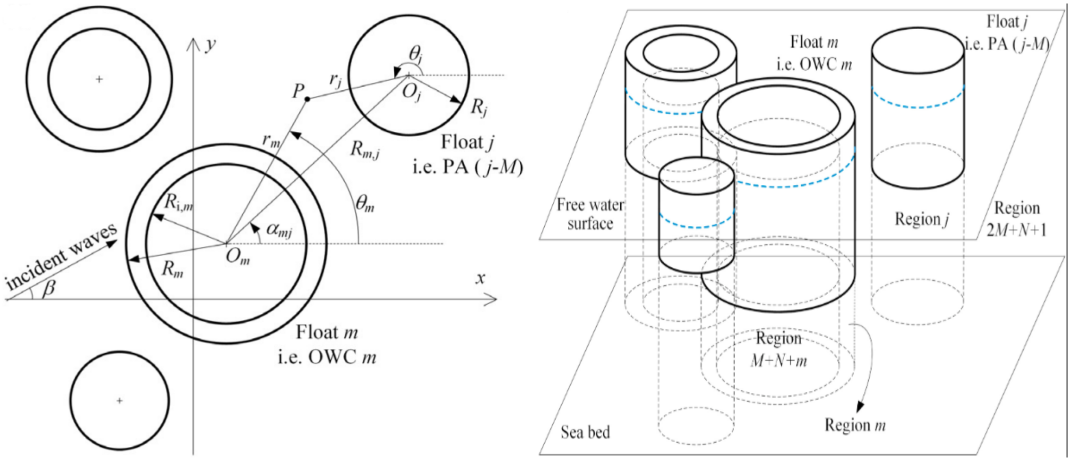


Figure 9. Dual chamber OWC ([75] 2015).

[76] provided an effective theoretical framework to investigate the efficacy of a free-floating array of OWC, showing substantial improvements in recovered power for arrays spaced apart within the water columns. The hydrodynamic characteristics of a hybrid wave farm made up of both OWCs and point-absorber WECs were assessed in the studies [77,78] (Figure 10). [34] considered the analysis of a 3D water column by employing Bessel and modified Bessel functions in cylindrical coordinates. The impact of the frequency ratio—that is, the ratio of the device's natural frequency to the wave frequency—on the operation of a moored OWC device was examined by [79]. [71] utilized a CFD tool to study the effect of connection type and the angle between the float arm and the float in an octagonal truss-type structure integrated with multiple WECs. The array of cylinder OWC was modeled by [80] using a second-order time-domain higher-order boundary element method (BEM) (see Figure 11). The impact of wave load excitation on the U-OWC structure during extreme wave events was studied experimentally by [81]. [82] conducted a numerical study to determine the hydrodynamic efficiency of an OWC device for using sea waves to generate electricity in both regular and irregular wave settings.



(**a**) Plan view (**b**) Bird view

Figure 10. Hybrid wave farm [77].

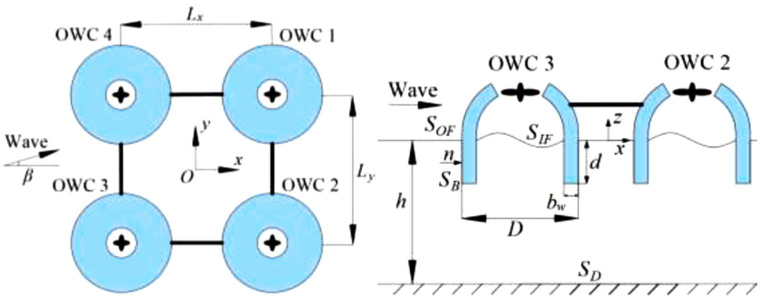


Figure 11. Quad OWC platform ([80] 2022).

In real sea environments, the irregular nature of incoming waves necessitates analyzing the performance of oscillating water column wave energy converters (OWC-WECs) under random wave conditions. [83] conducted experimental research focusing on an OWC-WEC positioned above an underwater mound. [84] explored the functioning of OWC-WECs across various seabed profiles (flat, sloping, curved), concluding that the efficiency of these systems increases with reduced wave steepness due to seabed shapes and increased flow, particularly in deeper waters. [85] introduced a dual-mass system to assess the hydrodynamic performance of OWC-WECs, highlighting the positive impact of stepped bottoms on efficiency, particularly in facing irregular incoming waves. [86] specifically examined an L-shaped OWC-WEC's performance under random wave conditions, emphasizing the significant influence of submergence depth on both the amplification factor and hydrodynamic efficiency. [87] used a 1:15 model to experimentally analyze OWC-WEC performance under random waves, noting the direct influence of wave spectrum on the chamber's spectral shape within the OWC-WEC. [88] investigated breakwater-integrated floating WECs under potential theory assumptions, highlighting the crucial role of the seaside wall in improving hydrodynamic performance. In a recent study, [89] explored OWC-WEC performance integrated with a cylindrical caisson breakwater, demonstrating substantial optimization potential, with peak efficiency reaching up to 81% under specific designs.

4. Recent Sea-Tested OWC Prototypes and Plants

The Kaimei floating vessel in Japan was one of the first OWC prototypes to be placed into the ocean in the 1970s. As shown in Figure 12, a fixed offshore plant was built in 2016 close to the shore of Jeju Island, South Korea. These facilities are equipped with two 250 kW rated power self-rectifying axial-flow impulse turbines. Since the beginning of wave energy technology, integrating wave energy converters into harbor safety structures has been considered a desirable alternative. This approach makes construction, installation, and maintenance easier and incorporates cost-sharing for structures with many uses. In Mutriku Harbor in Spain's Basque Country, a breakwater with sixteen OWCs was constructed. As shown in Figure 13, this facility, which was completed in 2012, was outfitted with sixteen bi-plane Wells turbine–generator sets, each powered at 18.5 kW.

Figure 12. Bottom-mounted OWC, Jeju island, South Korea ([90] 2022).

Figure 13. Mutriku harbor breakwater.

In the port of Civitavecchia, Italy, a considerably larger breakwater with 124 OWCs was built; the project was finished in 2016 (as shown in Figure 14). Initially, only one turbine of the bi-plane Wells type was temporarily installed. The Civitavecchia OWCs, designed by [91], have a U-shaped form that enables a longer OWC that can easily attain resonance, all the while maintaining the mouth close to the sea surface (as depicted in Figure 15). The concept of U-OWC breakwaters is intended for replication in other locations in Italy. Recently, in Portland, Oregon, USA, a life-sized prototype was constructed to deploy it in Hawaii (as illustrated in Figure 16).

The spar-buoy OWC converter is another version of the floating OWC idea. It is made up of an axisymmetric float with an extended coaxial vertical tube that opens to the sea at its lower end, containing the water column. This concept has been subject to thorough theoretical, numerical, and wave tank studies in recent years. In the Basque Country, Spain, at the BiMAP test site, a scaled-down prototype of around one-third its original size was built and tested in 2018 and 2019. An air turbine that was 30 kW bi-radial and self-rectifying was installed on the converter. The turbine–generator combination had already gone through a year-long testing phase at one of the OWCs inside the Mutriku breakwater. Additionally, in 2018–2019, the MARMOK-A-5 spar-buoy OWC was equipped with a 30 kW biradial turbine that had been tested at Mutriku. This turbine was then placed in the BiMAP test site in the Basque Country, Spain (as shown in Figure 17).

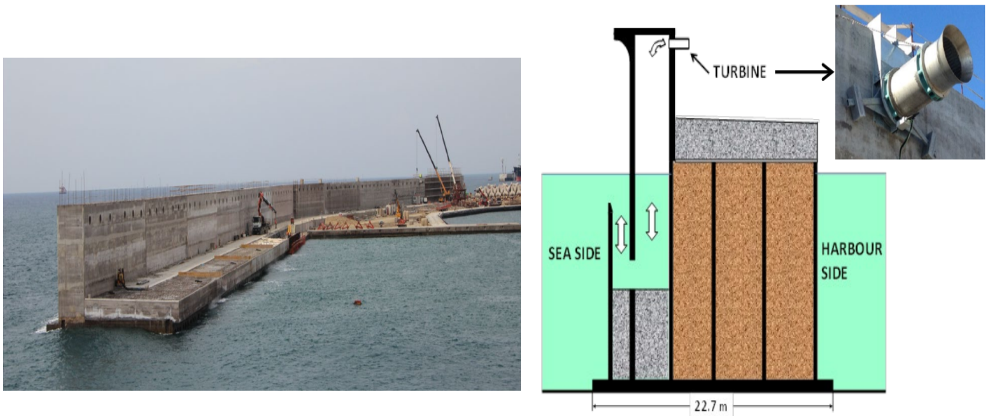
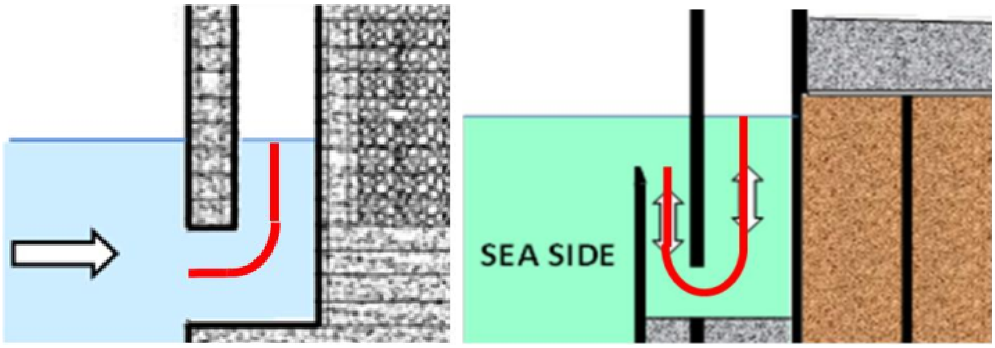


Figure 14. Breakwater at Civitavecchia ([90] 2022).



(**a**) Mutriku (**b**) Civitavecchia

Figure 15. Cross-section of the Mutriku conventional OWC and the U-shaped OWC of Civitavecchia breakwater ([90] 2022).

Figure 16. Full-sized prototype in Portland, (2019) [90] 2022.

In the case of the spar-buoy tube, the lower opening is positioned at a significant depth below the sea surface, typically around 30 m. Consequently, the absorption of wave energy primarily occurs through the interaction between the oscillating float and the surrounding waves. Alternatively, as seen in Figure 18, the co-axial tube OWC offers a situation that is similar to an axisymmetric floating form of Boccotti's U-OWC. The tube's upward-facing aperture in this configuration is located close to the water surface. Furthermore, the hydrostatic restoring force is also relatively low because of the small water plane area, which is the annular cross-sectional area of the inner tube wall at seawater surface level. The floating structure acts as a semi-submersible structure, and as a result, the frequency of its free oscillations is also small. This unique characteristic results in weak excitation of heave and pitch oscillations by sea waves, making this type of WEC suitable for integration into multi-use floating platforms. Within the scope of the H2020 project, WETFEET, a group consisting of five of these OWCs—rigidly connected in an array—underwent model testing in 2017 (as shown in Figure 18). Most recently, [92] studied the effect of an array of arbitrary trenches on the slanted OWC attached to an impermeable sea wall.

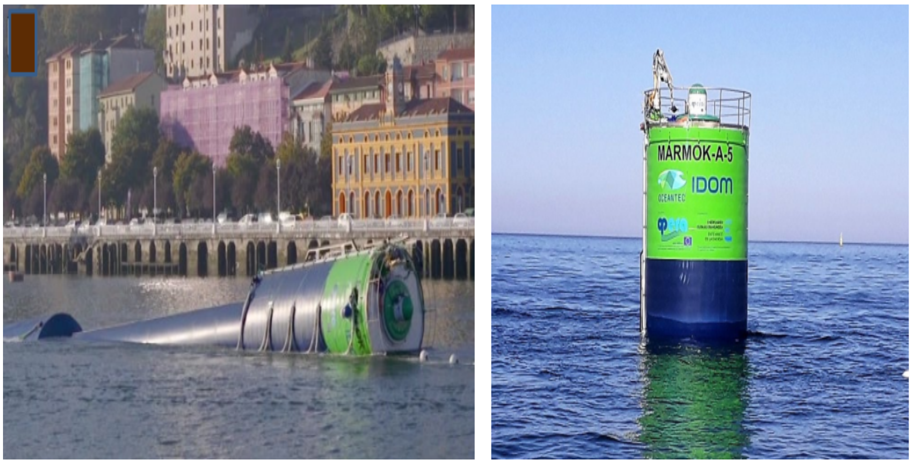
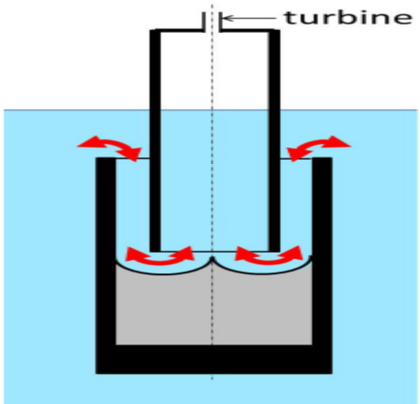
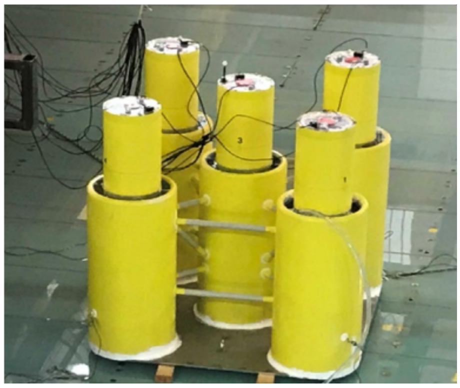


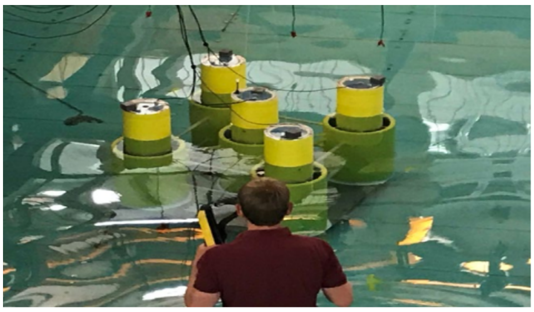
Figure 17. MARMOK-A-5 spar-buoy OWC Spain [90]).



(**a**) Co-axial-tube



(**b**) Array model



(**c**) Experimental Testing of Array in the Wave Tank

Figure 18. University of Plymouth (2017) [90] 2022).

5. Computational Fluid Dynamic (CFD)

Wave energy converters represent a modest yet theoretically significant segment of the global renewable energy portfolio. However, for the WEC industry to be competitive with offshore wind or solar energy, it must advance viable prototypes that can be upscaled for commercial deployment. To effectively assess performance indicators during the initial design stages, the adoption of robust and reliable numerical modeling methods is imperative. CFD algorithms, capable of solving Navier–Stokes equations (NSEs) or addressing Reynolds-averaged Navier–Stokes (RANS) problems, offer the means to handle intricate nonlinearities that may pose challenges for other approaches. The three most commonly utilized approaches for numerical modeling of WECs include the linear and nonlinear potential flow approach, the fully non-linear potential flow technique, and the CFD method, which can solve the NSE for both single and two-phase fluids. Accurately modeling the two-phase fluid interface in the chamber where air and water interact is one of the primary challenges with the CFD approach.

CFD simulations of oscillating water column (OWC) systems allow for a quantitative assessment of their energy and power performance potentials. Through computational modeling, we derive estimations of the mean annual energy production (AEP) based on wave interactions with the OWC chamber. This calculation typically yields values in kilowatt-hours (kWh) per unit area, providing an estimate of the average energy output over a defined period. Furthermore, CFD analyses facilitate the determination of the instantaneous power output by evaluating air movement within the chamber during different wave conditions. Additionally, conversion efficiency, expressed as a percentage, can be quantified by assessing the system's ability to convert incident wave power into usable electricity.

A crucial aspect impacting the power potential of OWC systems lies in the multiple zero crossings during a wave's period, directly influencing force and velocity interactions. In the realm of CFD, zero crossings during a wave's period present intricate challenges impacting force–velocity interactions within OWC systems. CFD simulations enable the visualization and quantification of these fluctuations in force and velocity. These moments of minimal or zero force and velocity pose a challenge to sustained power generation, requiring specialized attention to optimize energy extraction. The simulations facilitate a detailed understanding of how these fluctuations affect the pressure differentials and airflow rates crucial for power generation. By quantifying these impacts, strategies can be formulated to enhance energy capture during these critical intervals. Utilizing CFD-derived insights, design modifications can be proposed to mitigate the adverse effects of zero crossings. Tailoring the chamber's geometry or implementing adaptive mechanisms, informed by CFD predictions, can optimize energy capture during these transient periods. CFD simulations also aid in evaluating the effectiveness of control strategies, such as dynamically adjusting the chamber configuration or air column response and maximizing energy extraction despite zero crossings.

In a study conducted by [93], a two-dimensional CFD simulation verified through experimentation and implemented using Fluent software was employed to assess the impact of the frontal lip of the OWC chamber on the device's hydrodynamic performance. In reference to [93], it was observed that making minor modifications to the frontal wall of the chamber, such as increasing its thickness or introducing curvature, can lead to substantial enhancements in the effectiveness of the OWC. [94] employs an innovative approach for the three-dimensional modeling of an OWC that addresses the interaction between waves and the structure (Figure 19). Using CFD simulations, the RANS equations for two incompressible phases—air and water—must be solved. CFD findings for airflow velocity with time are shown in Figure 20 by [94].

A 3D CFD model was also created by [95] using the NSE to investigate the hydrodynamics of a bottom-mounted OWC mechanism. Their research revealed that vortex shedding greatly enhances the spatial resolution of the OWC cylinder. [95] presents a 3D depiction of the simulation of OWC and wave height patterns inside the OWC cylinder, which is shown in Figure 21.

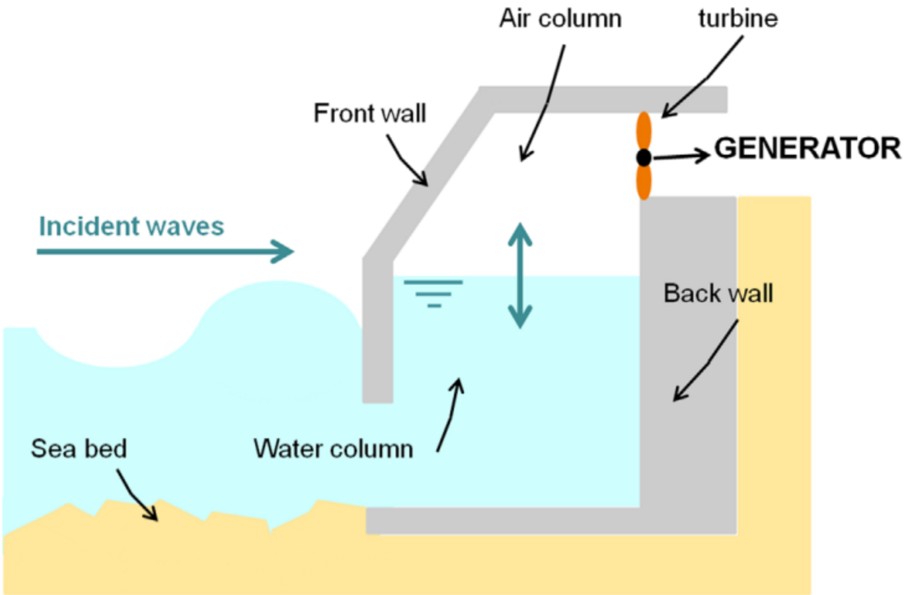


Figure 19. The oscillating water column scheme ([94] 2015).

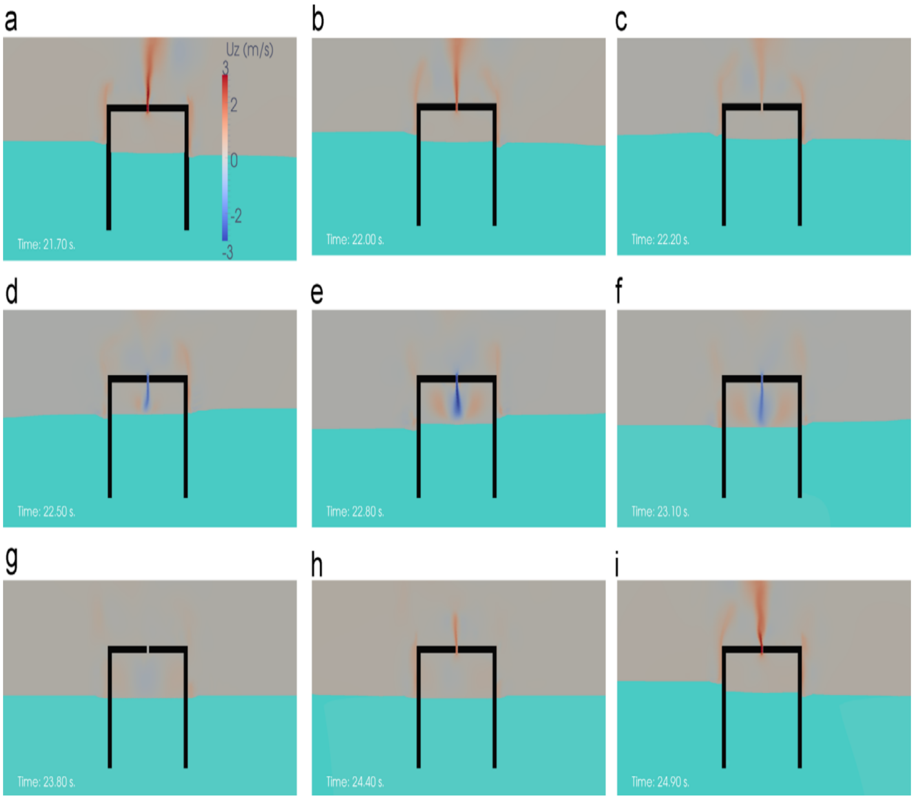
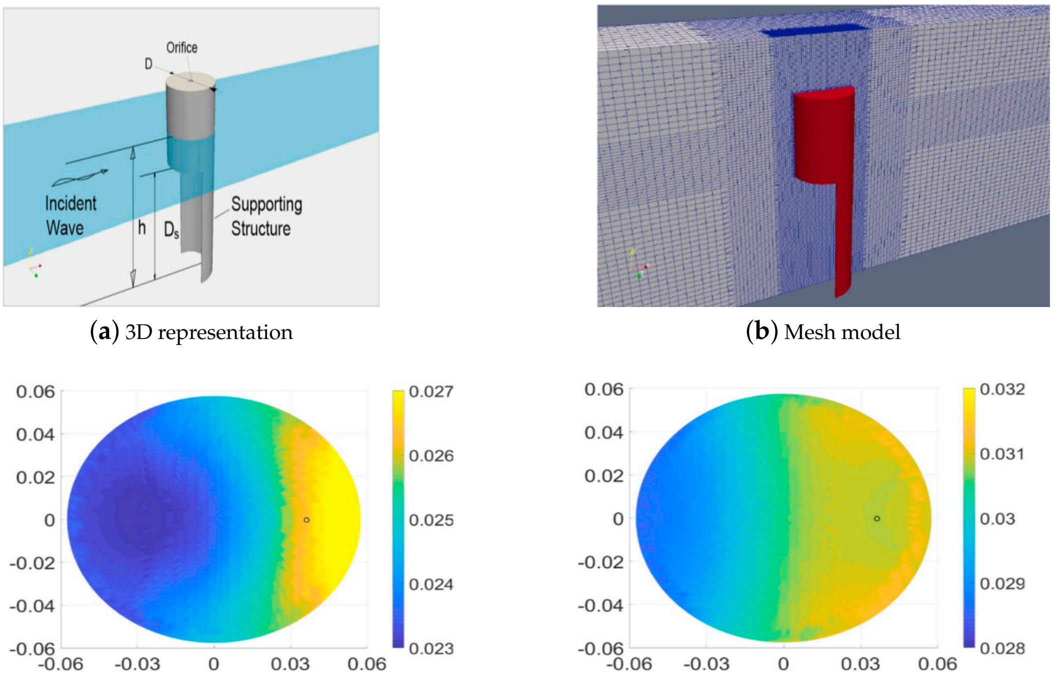


Figure 20. The vertical air velocity within the chamber throughout a pressurization–depressurization cycle (**a**) t = 21.70 s; (**b**) t = 22.00 s; (**c**) t = 22.20 s; (**d**) t = 22.50 s; (**e**) t = 22.80 s; (**f**) t = 23.10 s; (**g**) t = 23.80 s; and (**h**) t = 24.40 s; and (**i**) t = 24.90 s ([94] 2015).



(**a**) 3D representation (**b**) Mesh model

(**c**) Wave height patterns for 0.7s time passed (**d**) Wave height patterns for 0.8s time passed

Figure 21. OWC simulation ([95] 2019).

In reference to [96], a 3D CFD method for assessing stationary multi-chamber OWC equipment was introduced, and the CFD results have been demonstrated to align with experimental findings. In order to effectively decrease the expenses associated with OWCs, [97] examined the potential for structural optimization. They analyzed an OWC in a three-dimensional space with an extra vertical channel employing a one-way coupled hydraulic-structural numerical simulation. This design encompassed both a fluid and a solid domain. The study found that a 2D model might be appropriate for feasibility studies by removing the solid domain and making use of the feature that water pressures display homogeneity over the transverse width, significantly simplifying the simulation. Their results are shown in Figure 22, where maximum inflow conditions are shown in the top row and maximum outflow circumstances are shown in the bottom row.

The efficacy of a novel hybrid WEC device that combines an overtopping device and an OWC inside a rubble mound structure was investigated by [98]. Based on the findings of a physical model research carried out at a geometric scale of 1:50, this assessment was made. The device's performance was optimized by numerical simulations using ANSYS Fluent prior to the experimental observations. The effectiveness of both capture methods was assessed, and the hybrid WEC's ability to capture wave power was calculated. The research demonstrated that across a broader range of wave circumstances, the hybridization of these technologies might produce more effective outcomes than each of them individually. Later, using the CFD program OpenFOAM, [99] carried out a numerical investigation to examine the hydrodynamic properties of an OWC device linked with a submerged horizontal sheet.

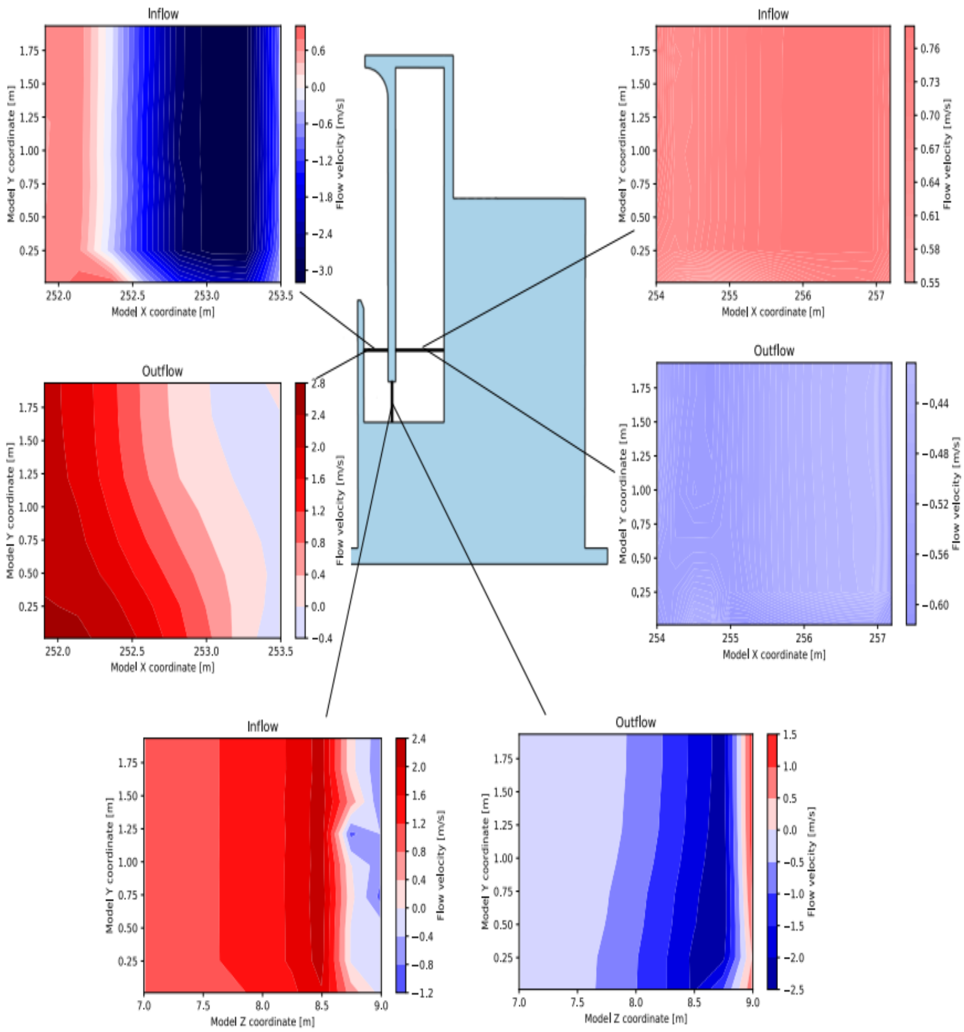


Figure 22. The flow velocity pattern within the cylinder ([97] 2021).

6. Conclusions

In this paper, we conducted a comprehensive analysis of research gaps to gain insights into the current trends in the field of WECs and OWCs. The research demonstrates that numerous opportunities exist for optimizing the design of OWCs, exploring diverse deployment methods, implementing multi-functional OWCs, and innovating wave and wind energy harnessing techniques. It also emphasizes how simple the OWC WEC is to use in capturing wave energy, with its few moving parts, low complexity, and adaptability to be integrated into various other WECs or even complementary renewable energy sources like wind turbines. The goal is to offer researchers a well-defined path for selecting the most suitable method for their project implementation.

Substantial advancements have been made since the introduction of early self-rectifying air turbines, namely the axial-flow Wells and impulse turbines, in the mid-1970s. Model testing indicates that modern turbine designs can achieve peak efficiencies of approximately 80% and average efficiencies above 70% in random wave conditions. This positions the air turbine PTO system in direct competition with high-pressure hydraulic circuits or direct electrical energy conversion utilizing linear generators. In the near future, it is equitable to anticipate that efficiencies comparable to those of more conventional turbines, such as steam, gas, and hydraulic turbines, will be obtained.

The primary approach commonly utilized for theoretical hydrodynamic modeling of OWC relies on linear water wave theory and hydrodynamic coefficients, particularly when conducting control studies. The Reynolds-averaged Navier–Stokes (RANS) equations are the foundation of many computational fluid dynamics (CFD) methods, while their use is frequently limited to two-dimensional configurations and regular wave conditions. Similar to other wave energy converters, a crucial stage in OWC development involves model testing, typically conducted in wave tanks or wave flumes. However, addressing the air chamber's compressibility effect and accurately simulating the air turbine in model testing presents specific challenges that have not always been adequately resolved. Phase control represents a domain where significant enhancements in power efficiency and economic feasibility can be anticipated with only marginal additional expenses. For OWC, latching-based phase control emerges as the most feasible approach, although certain mathematical control challenges must be adequately addressed before practical implementation.

Author Contributions: Conceptualization, J.-Y.C., C.-C.T. and T.-W.H.; methodology, J.-Y.C.; data curation, J.-Y.C. and R.G.; writing—original draft preparation, R.G. and C.-C.T.; supervision, C.-C.T. and T.-W.H.; project administration, T.-W.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Science and Technology Council of Taiwan under grant no. NSTC 112-2221-E-019-050-MY3.

Institutional Review Board Statement: Not applicable

Informed Consent Statement: Not applicable

Data Availability Statement: Not applicable

Acknowledgments: CC Tsai gratefully acknowledges the financial support from the National Science and Technology Council of Taiwan.

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

References

1. Ross, D. Power from the Waves. *Annu. Rev. Fluid Mech.* **1995**, *13*, 157–187.
2. McCormick, M.E. *Ocean Wave Energy Conversion*; Courier Corporation: North Chelmsford, MA, USA, 2013.
3. Shaw, R. *Wave Energy—A Design Challenge*; University of Liverpool, Department of Mechanical Engineering, Ellis Horwood Ltd. Publishers: Chichester, UK, 1982; ISBN 0-85312-382-9.
4. Charlier, R.H.; Justus, J.R. Ocean Energies: Environmental, Economic and Technological Aspects of Alternative Power Sources; Elsevier: Amsterdam, The Netherlands, 1993.
5. Brooke, J. *Wave Energy Conversion*; Elsevier: Amsterdam, The Netherlands, 2003.
6. Cruz, J. *Ocean Wave Energy: Current Status and Future Prespectives*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2007.
7. Thorpe, T. *A Brief Review of Wave Energy: A Report Produced for the UK*; ETSU-R120, May; Department of Trade and Industry: London, UK, 1999.
8. WaveNet. Results from the Work of the European Thematic Network on Wave Energy. 2003. Available online: https://cordis.europa.eu/docs/projects/files/ERK5/ERK5-CT-1999-20001/66682851-6_en.pdf (accessed on 9 February 2024).
9. Salter, S.H. World progress in wave energy—1988. *Int. J. Ambient. Energy* **1989**, *10*, 3–24. [CrossRef]
10. Thorpe, T. An overview of wave energy technologies: Status, performance and costs. In *Wave Power: Moving Towards Commercial Viability*; Wiley: Hoboken, NJ, USA, 1999; Volume 26, pp. 50–120.
11. Clément, A.; McCullen, P.; Falcão, A.; Fiorentino, A.; Gardner, F.; Hammarlund, K.; Lemonis, G.; Lewis, T.; Nielsen, K.; Petroncini, S.; et al. Wave energy in Europe: Current status and perspectives. *Renew. Sustain. Energy Rev.* **2002**, *6*, 405–431. [CrossRef]
12. Falcão, A.d.O. First-generation wave power plants: Current status and R&D requirements. In Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering, Cancun, Mexico, 8–13 June 2003; Volume 36835, pp. 723–731.
13. Falnes, J. A review of wave-energy extraction. *Mar. Struct.* **2007**, *20*, 185–201. [CrossRef]
14. Masuda, Y. *Wave-Activated Generator*; International College on the Expositions of the Oceans (Transaction): Bordeaux, France, 1971.
15. Masuda, Y. Experimental full-scale results of wave power machine Kaimei in 1978. In Proceedings of the First Symposium Wave Energy Utilization, Gothenburg, Sweden, 30 October–1 November 1979; pp. 349–363.
16. Salter, S.H. Wave Power. *Nature* **1974**, *249*, 720–724. [CrossRef]
17. Grove-Palmer, C. Wave energy in the United Kingdom: A review of the programme June 1975–March 1982. In Proceedings of the The Second International Symposium on Wave Energy Utilization (Trondheim), Trondheim, Norway, 22–24 June 1982.
18. Whittaker, T.; Raghunathan, S. Islay European Shoreline Wave Power Station. In Proceedings of the First European Wave Energy Symposium, Edinburgh, Scotland, 21–24 July 1993; pp. 21–24.

19. Ohneda, H.; Igarashi, S.; Shinbo, O.; Sekihara, S.; Suzuki, K.; Kubota, H.; Morita, H. Construction procedure of a wave power extracting caisson breakwater. In Proceedings of the 3rd Symposium on Ocean Energy Utilization, Tokyo, Japan, 22–23 January 1991; pp. 171–179.
20. Ravindran, M.; Koola, P.M. Energy from sea waves—The Indian wave energy programme. *Curr. Sci.* **1991**, *60*, 676–680.
21. Falcão, A.F.d.O. Wave energy utilization: A review of the technologies. *Renew. Sustain. Energy Rev.* **2010**, *14*, 899–918. [CrossRef]
22. Xu, S.; Wang, S.; Soares, C.G. Review of mooring design for floating wave energy converters. *Renew. Sustain. Energy Rev.* **2019**, *111*, 595–621. [CrossRef]
23. Heath, T. A review of oscillating water columns. *Phil. Trans. R. Soc. A* **2012**, *370*, 235–245. [CrossRef] [PubMed]
24. Evans, D.; Porter, R. Hydrodynamic characteristics of an oscillating water column device. *Appl. Ocean. Res.* **1995**, *17*, 155–164. [CrossRef]
25. Deng, Z.; Huang, Z.; Law, A.W. Wave power extraction by an axisymmetric oscillating-water-column converter supported by a coaxial tube-sector-shaped structure. *Appl. Ocean. Res.* **2013**, *42*, 114–123. [CrossRef]
26. Porter, R.; Zheng, S.; Greaves, D. Extending limits for wave power absorption by axisymmetric devices. *J. Fluid Mech.* **2021**, *924*. [CrossRef]
27. Elhanafi, A.; Fleming, A.; Macfarlane, G.; Leong, Z. Numerical energy balance analysis for an onshore oscillating water column—Wave energy converter. *Energy* **2016**, *116*, 539–557. [CrossRef]
28. Michele, S.; Zheng, S.; Greaves, D. Wave energy extraction from a floating flexible circular plate. *Ocean. Eng.* **2022**, *245*, 110275. [CrossRef]
29. Wu, J.; Qin, L.; Chen, N.; Qian, C.; Zheng, S. Investigation on a spring-integrated mechanical power take-off system for wave energy conversion purpose. *Energy* **2022**, *245*, 123318. [CrossRef]
30. Hamamoto, T.; Tanaka, Y. Coupled free vibrational characteristics of artificial floating islands. Part 1.; Fluid-structure interaction analysis of floating elastic circular plate. Fuyushiki kaiyo jinkoto no rensei jiyu shindo tokusei. 1.; Fuyu dansei enban no ryutai-kozobutsu sogo sayo kaiseki. *Nippon Kenchiku Gakkai Kozokei Ronbun Hokokushu (J. Struct. Constr. Eng.)* **1992**, *438*, 165–177.
31. Montiel, F.; Bennetts, L.; Squire, V.; Bonnefoy, F.; Ferrant, P. Hydroelastic response of floating elastic discs to regular waves. Part 2. Modal analysis. *J. Fluid Mech.* **2013**, *723*, 629–652. [CrossRef]
32. Das, S.; Sahoo, T. Hydroelastic analysis of very large floating structure over viscoelastic bed. *Meccanica* **2017**, *52*, 1871–1887. [CrossRef]
33. Energy, A. Oscillating water column wave energy converter evaluation report. In *The Carbon Trust, Marine Energy Challenge*; Elsevier: Amsterdam, The Netherlands, 2005; pp. 1–196.
34. Zheng, S.; Antonini, A.; Zhang, Y.; Greaves, D.; Miles, J.; Iglesias, G. Wave power extraction from multiple oscillating water columns along a straight coast. *J. Fluid Mech.* **2019**, *878*, 445–480. [CrossRef]
35. Lehmann, M.; Karimpour, F.; Goudey, C.A.; Jacobson, P.T.; Alam, M.R. Ocean wave energy in the United States: Current status and future perspectives. *Renew. Sustain. Energy Rev.* **2017**, *74*, 1300–1313. [CrossRef]
36. Qiao, D.; Haider, R.; Yan, J.; Ning, D.; Li, B. Review of wave energy converter and design of mooring system. *Sustainability* **2020**, *12*, 8251. [CrossRef]
37. Setoguchi, T.; Takao, M. Current status of self rectifying air turbines for wave energy conversion. *Energy Convers. Manag.* **2006**, *47*, 2382–2396. [CrossRef]
38. Doyle, S.; Aggidis, G.A. Development of multi-oscillating water columns as wave energy converters. *Renew. Sustain. Energy Rev.* **2019**, *107*, 75–86. [CrossRef]
39. Delmonte, N.; Barater, D.; Giuliani, F.; Cova, P.; Buticchi, G. Oscillating water column power conversion: A technology review. In Proceedings of the 2014 IEEE Energy Conversion Congress and Exposition (ECCE), IEEE, Pittsburgh, PA, USA, 14–18 September 2014; pp. 1852–1859.
40. Lye, J.L.; Brown, D.T.; Johnson, F. An investigation into the non-linear effects resulting from air cushions in the Orecon oscillating water column (OWC) device. In Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering, Osaka, Japan, 21–26 June 2009; Volume 43444, pp. 779–789.
41. Dorrell, D.G.; Hsieh, M.F.; Lin, C.C. A multichamber oscillating water column using cascaded savonius turbines. *IEEE Trans. Ind. Appl.* **2010**, *46*, 2372–2380. [CrossRef]
42. Falcão, A.F.; Henriques, J.C.; Gato, L.M. Self-rectifying air turbines for wave energy conversion: A comparative analysis. *Renew. Sustain. Energy Rev.* **2018**, *91*, 1231–1241. [CrossRef]
43. Count, B.; Evans, D. The influence of projecting sidewalls on the hydrodynamic performance of wave-energy devices. *J. Fluid Mech.* **1984**, *145*, 361–376. [CrossRef]
44. Alcorn, R.; Hunter, S.; Signorelli, C.; Obeyesekera, R.; Finnigan, T.; Denniss, T. Results of the testing of the Energetech wave energy plant at Port Kembla. *Energeth Rep.* **2005**, *5*, 44.
45. Basmat, A.; Denniss, T.; Finnigan, T. Diffraction of linear water waves on a parabolic wall: Small parameter approach. In Proceedings of the ISOPE International Ocean and Polar Engineering Conference, ISOPE, Honolulu, HI, USA, 25–30 May 2003; p. ISOPE–I.
46. Martins, E.; Carrilho, L.; Neumann, F.; Ramos, F.S.; Justino, P.A.; Gato, L.; Trigo, L. Ceodouro project: Overall design of an OWC in the new OPorto break water. In Proceedings of the Conference: 6. EWTEC- European Wave and Tidal Energy Conference, Glasgow, UK, 29 August–2 September 2005.

47. Torre-Enciso, Y.; Ortubia, I.; De Aguileta, L.L.; Marqués, J. Mutriku wave power plant: From the thinking out to the reality. In Proceedings of the 8th European wave and tidal Energy Conference, Uppsala, Sweden, 7–10 September 2009; Volume 710, pp. 319–329.
48. Boccotti, P. Caisson breakwaters embodying an OWC with a small opening—Part I: Theory. *Ocean. Eng.* **2007**, *34*, 806–819. [CrossRef]
49. Boccotti, P.; Filianoti, P.; Fiamma, V.; Arena, F. Caisson breakwaters embodying an OWC with a small opening—Part II: A small-scale field experiment. *Ocean. Eng.* **2007**, *34*, 820–841. [CrossRef]
50. Masuda, Y.; McCormick, M.E. Experiences in pneumatic wave energy conversion in Japan. In Proceedings of the Coastal Engineering 1986, ASCE, Reston, VA, USA, 9–11 March 1986; pp. 1–33.
51. Masuda, Y.; Xianguang, L.; Xiangfan, G. High performance of cylinder float backward bent duct buoy (BBDB) and its use in European seas. In Proceedings of the (First) European Wave Energy Symposium, Enburgh, Scotland, 21–24 July 1993; pp. 323–337.
52. Masuda, Y.; Kimura, H.; Liang, X.; Gao, X.; Mogensen, R.; Anderson, T. Regarding BBDB wave power generation plant. In Proceedings of the 2nd European Wave Power Conference, Lisbon, Portugal, 8–10 November 1995; pp. 69–76.
53. Washio, Y.; Osawa, H.; Nagata, Y.; Fujii, F.; Furuyama, H.; Fujita, T. The offshore floating type wave power device "Mighty Whale": Open sea tests. In Proceedings of the ISOPE International Ocean and Polar Engineering Conference, ISOPE, Seattle, WA, USA, 27 May–2 June 2000; p. ISOPE–I.
54. Evans, D. A theory for wave-power absorption by oscillating bodies. *J. Fluid Mech.* **1976**, *77*, 1–25. [CrossRef]
55. Sarmento, A.J.; Falcão, A.d.O. Wave generation by an oscillating surface-pressure and its application in wave-energy extraction. *J. Fluid Mech.* **1985**, *150*, 467–485. [CrossRef]
56. Falnes, J.; McIver, P. Surface wave interactions with systems of oscillating bodies and pressure distributions. *Appl. Ocean. Res.* **1985**, *7*, 225–234. [CrossRef]
57. Konispoliatis, D.N. Performance of an array of oscillating water column devices in front of a fixed vertical breakwater. *J. Mar. Sci. Eng.* **2020**, *8*, 912. [CrossRef]
58. Konispoliatis, D.N.; Mavrakos, S.A. Hydrodynamic efficiency of a wave energy converter in front of an orthogonal breakwater. *J. Mar. Sci. Eng.* **2021**, *9*, 94. [CrossRef]
59. Pols, A.; Gubesch, E.; Abdussamie, N.; Penesis, I.; Chin, C. Mooring analysis of a floating OWC wave energy converter. *J. Mar. Sci. Eng.* **2021**, *9*, 228. [CrossRef]
60. Mohapatra, P.; Bhattacharyya, A.; Sahoo, T. Performance of a floating oscillating water column wave energy converter over a sloping bed. *Ships Offshore Struct.* **2021**, *16*, 659–669. [CrossRef]
61. Lovas, S.; Mei, C.C.; Liu, Y. Oscillating water column at a coastal corner for wave power extraction. *Appl. Ocean. Res.* **2010**, *32*, 267–283. [CrossRef]
62. Rezanejad, K.; Bhattacharjee, J.; Soares, C.G. Stepped sea bottom effects on the efficiency of nearshore oscillating water column device. *Ocean. Eng.* **2013**, *70*, 25–38. [CrossRef]
63. Wang, C.; Zheng, S.; Zhang, Y. A heaving system with two separated oscillating water column units for wave energy conversion. *Phys. Fluids* **2022**, *34*, 047103. [CrossRef]
64. Renzi, E. Hydroelectromechanical modelling of a piezoelectric wave energy converter. *Proc. R. Soc. Math. Phys. Eng. Sci.* **2016**, *472*, 20160715. [CrossRef]
65. Nader, J.R.; Zhu, S.P.; Cooper, P.; Stappenbelt, B. A finite-element study of the efficiency of arrays of oscillating water column wave energy converters. *Ocean. Eng.* **2012**, *43*, 72–81. [CrossRef]
66. Zheng, S.; Meylan, M.; Greaves, D.; Iglesias, G. Water-wave interaction with submerged porous elastic disks. *Phys. Fluids* **2020**, *32*, 047106. [CrossRef]
67. Zheng, S.; Meylan, M.H.; Zhu, G.; Greaves, D.; Iglesias, G. Hydroelastic interaction between water waves and an array of circular floating porous elastic plates. *J. Fluid Mech.* **2020**, *900*, A20. [CrossRef]
68. Trivedi, K.; Koley, S. Performance of a hybrid wave energy converter device consisting of a piezoelectric plate and oscillating water column device placed over an undulated seabed. *Appl. Energy* **2023**, *333*, 120627. [CrossRef]
69. Zheng, S.; Phillips, J.W.; Hann, M.; Greaves, D. Mathematical modelling of a floating Clam-type wave energy converter. *Renew. Energy* **2023**, *210*, 280–294. [CrossRef]
70. Wang, C.; Deng, Z.; Wang, P. Numerical investigation of dual-owc-devices system composed by offshore and onshore unit. In *International Conference on Asian and Pacific Coasts*; Springer: Berlin/Heidelberg, Germany, 2019; pp. 107–114.
71. He, G.; Luan, Z.; Jin, R.; Zhang, W.; Wang, W.; Zhang, Z.; Jing, P.; Liu, P. Numerical and experimental study on absorber-type wave energy converters concentrically arranged on an octagonal platform. *Renew. Energy* **2022**, *188*, 504–523. [CrossRef]
72. McIver, P.; Evans, D. Approximate theory for the performance of a number of wave-energy devices set into a reflecting wall. *Appl. Ocean Res.* **1988**, *10*, 58–65. [CrossRef]
73. Thiruvenkatasamy, K.; Neelamani, S. On the efficiency of wave energy caissons in array. *Appl. Ocean. Res.* **1997**, *19*, 61–72. [CrossRef]
74. Falcão, A.d.O. Wave-power absorption by a periodic linear array of oscillating water columns. *Ocean. Eng.* **2002**, *29*, 1163–1186. [CrossRef]
75. Rezanejad, K.; Bhattacharjee, J.; Soares, C.G. Analytical and numerical study of dual-chamber oscillating water columns on stepped bottom. *Renew. Energy* **2015**, *75*, 272–282. [CrossRef]

76. Konispoliatis, D.; Mavrakos, S. Hydrodynamic analysis of an array of interacting free-floating oscillating water column (OWC's) devices. *Ocean. Eng.* **2016**, *111*, 179–197. [CrossRef]
77. Zheng, S.; Zhang, Y.; Iglesias, G. Wave–structure interaction in hybrid wave farms. *J. Fluids Struct.* **2018**, *83*, 386–412. [CrossRef]
78. Zheng, S.; Zhang, Y. Theoretical modelling of a new hybrid wave energy converter in regular waves. *Renew. Energy* **2018**, *128*, 125–141. [CrossRef]
79. Mia, M.R.; Zhao, M.; Wu, H.; Dhamelia, V.; Hu, P. Hydrodynamic Performance of a Floating Offshore Oscillating Water Column Wave Energy Converter. *J. Mar. Sci. Eng.* **2022**, *10*, 1551. [CrossRef]
80. Zhou, Y.; Ning, D.; Liang, D.; Qiao, D. Nonlinear wave loads on an offshore oscillating-water-column wave energy converter array. *Appl. Ocean. Res.* **2022**, *118*, 103003. [CrossRef]
81. Romolo, A.; Timpano, B.; Laface, V.; Fiamma, V.; Arena, F. Experimental Investigation of Wave Loads on U-OWC Breakwater. *J. Mar. Sci. Eng.* **2023**, *11*, 19. [CrossRef]
82. Cannata, G.; Simone, M.; Gallerano, F. Numerical Investigation into the Performance of an OWC Device under Regular and Irregular Waves. *J. Mar. Sci. Eng.* **2023**, *11*, 735. [CrossRef]
83. Gouaud, F.; Rey, V.; Piazzola, J.; Van Hooff, R. Experimental study of the hydrodynamic performance of an onshore wave power device in the presence of an underwater mound. *Coast. Eng.* **2010**, *57*, 996–1005. [CrossRef]
84. Ashlin, S.J.; Sundar, V.; Sannasiraj, S. Effects of bottom profile of an oscillating water column device on its hydrodynamic characteristics. *Renew. Energy* **2016**, *96*, 341–353. [CrossRef]
85. Rezanejad, K.; Soares, C.G. Enhancing the primary efficiency of an oscillating water column wave energy converter based on a dual-mass system analogy. *Renew. Energy* **2018**, *123*, 730–747. [CrossRef]
86. Rezanejad, K.; Souto-Iglesias, A.; Soares, C.G. Experimental investigation on the hydrodynamic performance of an L-shaped duct oscillating water column wave energy converter. *Ocean. Eng.* **2019**, *173*, 388–398. [CrossRef]
87. Zabihi, M.; Mazaheri, S.; Namin, M.M. Experimental hydrodynamic investigation of a fixed offshore Oscillating Water Column device. *Appl. Ocean. Res.* **2019**, *85*, 20–33. [CrossRef]
88. Zhang, Y.; Li, M.; Zhao, X.; Chen, L. The effect of the coastal reflection on the performance of a floating breakwater-WEC system. *Appl. Ocean. Res.* **2020**, *100*, 102117. [CrossRef]
89. Chen, J.; Wen, H.; Wang, Y.; Ren, B. Experimental investigation of an annular sector OWC device incorporated into a dual cylindrical caisson breakwater. *Energy* **2020**, *211*, 118681. [CrossRef]
90. Falcão, A. Overview on oscillating water column devices. In *Floating Offshore Energy Devices: GREENER*; Materials Research Forum LLC.: Millersville, PA, USA, 2022; Volume 20.
91. Boccotti, P. Comparison between a U-OWC and a conventional OWC. *Ocean. Eng.* **2007**, *34*, 799–805. [CrossRef]
92. Gayathri, R.; Chang, J.Y.; Tsai, C.C. Wave power extraction from slanted oscillating water columns in the presence of an array of arbitrary trenches. *Phys. Fluids* **2023**, *35*, 97105. [CrossRef]
93. Horko, M. CFD Optimisation of an Oscillating Water Column Wave Energy Converter. Ph.D. Thesis, University of Western Australia, Crawley, WA, Australia, 2007.
94. Iturrioz, A.; Guanche, R.; Lara, J.; Vidal, C.; Losada, I. Validation of OpenFOAM® for oscillating water column three-dimensional modeling. *Ocean. Eng.* **2015**, *107*, 222–236. [CrossRef]
95. Xu, C.; Huang, Z. Three-dimensional CFD simulation of a circular OWC with a nonlinear power-takeoff: Model validation and a discussion on resonant sloshing inside the pneumatic chamber. *Ocean. Eng.* **2019**, *176*, 184–198. [CrossRef]
96. Shalby, M.; Elhanafi, A.; Walker, P.; Dorrell, D.G. CFD modelling of a small–scale fixed multi–chamber OWC device. *Appl. Ocean. Res.* **2019**, *88*, 37–47. [CrossRef]
97. Goeijenbier, B.; Bricker, J.; Antonini, A.; Malara, G.; Hendriks, M.; van der Ham, H. Structural Optimisation and Behaviour of the Breakwater Integrated Oscillating Water Column Device: A combined 3D CFD and Structural FEM Analysis. *J. Coast. Hydraul. Struct.* **2021**, *1*.
98. Cabral, T.; Clemente, D.; Rosa-Santos, P.; Taveira-Pinto, F.; Morais, T.; Belga, F.; Cestaro, H. Performance assessment of a hybrid wave energy converter integrated into a harbor breakwater. *Energies* **2020**, *13*, 236. [CrossRef]
99. Wang, C.; Zhang, Y. Hydrodynamic performance of an offshore Oscillating Water Column device mounted over an immersed horizontal plate: A numerical study. *Energy* **2021**, *222*, 119964. [CrossRef]