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Review

Floating Oscillating Water Column Wave Energy Converters: A Review of Developments

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Abstract

The main challenge in designing offshore renewable energy structures is to ensure their structural integrity on a life cycle basis while operating in harsh environments and, in parallel, being financially competitive and environmentally friendly concerning other types of energy systems. The Oscillating Water Column (OWC) converters are among the first energy converters to be developed and deployed into the sea due to their relative simplicity of operation and relatively small number of moving parts. This review provides an overview of the recent floating OWC prototypes and projects and the latest research developments in wave energy conversion using the oscillating water column principle. Furthermore, critical structural advances are discussed, mainly focusing on the converter's geometry and type and its mooring system design towards amplifying the absorbed wave power.

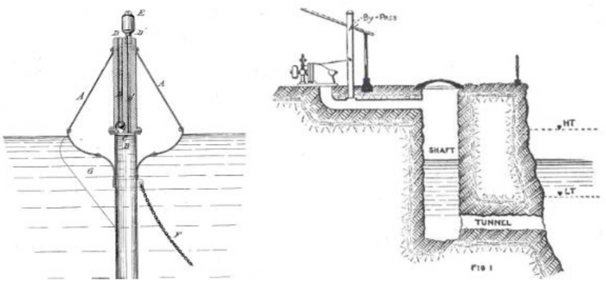
Keywords

Oscillating water column; OWC; WEC; floating

1. Introduction

Wave energy is an abundant renewable source that can provide utility-scale power production by capturing the movement of the ocean and sea waves. Mork et al. [1] cited 29,500 TWh/yr as the theoretical potential of wave energy, which can be mainly found between 30° and 60° latitude and in deep water (>40 meters) locations [2]. The possibility of converting wave energy into usable energy has inspired numerous inventors. Considerable progress has been made globally over the last 30 years, resulting in some technologies being at, or near, commercialization. In contrast, others require further R&D. However, wave energy technologies have not seen a convergence towards one type of design, as has happened in other renewable technologies such as wind energy. According to McCormick [3], more than one thousand patents have been registered by 1980, and the number has remarkably increased since then [4], including Oscillating Water Column devices, oscillating bodies, and overtopping devices, among others.

The first known patent to extract energy from ocean waves was in 1799 by Girard and his son, as mentioned by Clement et al. [5]. Also, in 1878, the pilots of the New York and Boston streamers recorded whistling buoys [6] used as a navigation aid (see Figure 1a). In 1895, Isidoro Cabanyes, a Spanish engineer, received a patent for a wave-powered device that used floats to pump water into a reservoir, releasing it to generate electricity [7]. Bochaux-Praceique constructed an early device around 1910 to power a house near Bordeaux in France (see Figure 1b). The oscillating water column wave energy technology [8] served as the basis for this device. Since then, numerous patents have been filed worldwide. According to [9] the ocean energy technology patents show unequal growth since 1900 with four main faces: (a) years 1900-1930 with the first take-off patents mainly from individual inventors; (b) years 1930-1970 with a sharp slowdown of patents due to the exclusion effect of the petrochemical paradigm; (c) years 1970-1995 with increased growth, followed by a downward trend to 1995; and (d) years 1995-2015 with a sharp continuous rise in wave energy patents. Figure 2 presents this phase breakdown from 1900 up to 2015. Until 2025, 19,276 patents have been received for ocean and offshore wind technologies [9].



(a) (b)

Figure 1 First known patents to extract energy from ocean waves: (a) whistling buoy patented by J.M. Courtney (adopted from Ref. [6]); (b) Bochaux-Praceique power system (adopted from Ref. [10]).

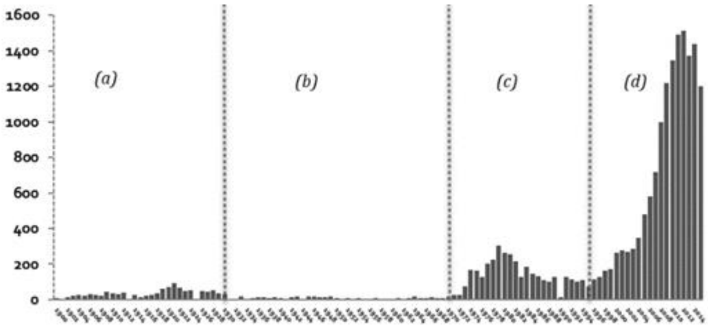


Figure 2 Number of patent families by priority year for ocean energy technologies over 1900-2015 (adopted from Ref. [9]).

In 2022, the global cumulative installed capacity for wave energy reached 24.9 MW, 12.7 MW in European sea basins, whereas the new installations accounted for 33.5 kW [11]. EU Joint Research Centre [12] estimated that the Levelized Cost of Energy (LCOE) for wave energy in 2019 ranged between 0.47 EUR/kWh and 1.4 EUR/kWh. Today (i.e., 2023), these values range between 0.3 EUR/kWh and 1.2 EUR/kWh [13]. Even if measured in different currencies, the wave energy LCOE sits in a range of 0.18-0.87 USD/kWh, whereas that of offshore wind varies from 0.1 to 0.56 USD/kWh, and solar energy varies from 0.06 to 0.38 USD/kWh. Nevertheless, continued technology development and advancements in the learning curve are expected to reduce the wave energy LCOE to 0.15 EUR/kWh by 2030 and 0.10 EUR/kWh by 2035 [14].

Despite the considerable variation in design, one can characterize wave energy converters (WECs) by location and type [15]. Specifically, one can categorize WECs by location concerning the shoreline, i.e., onshore, nearshore, and offshore. Concerning their type, we can classify WECs into three predominant types: (a) attenuator, (b) point absorber, and (c) terminator. Within these categories, WECs can be further classified based on their mode of operation, i.e., submerged pressure differential, oscillating wave surge converter, wave-activated body, overtopping device, rotating mass, bulge wave, and oscillating water column [16]. The European Marine Energy Centre (EMEC) offers a comprehensive compilation of worldwide wave energy developers. According to the latest update (August 2020) [17], the point absorbers represent one-third of the total known devices, followed by attenuators, over-topping, and oscillating water column converters. Figure 3 depicts the distribution of wave energy technologies according to EMEC's WEC classification [17].

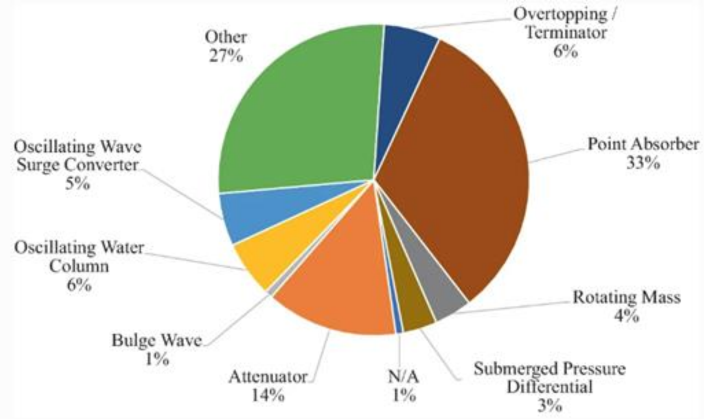


Figure 3 Distribution of wave energy technologies according to EMEC's WEC classification (adopted from Ref. [17]).

An Oscillating Water Column (OWC) device extracts wave energy using the rise and fall of waves into airflow through turbines to generate power. The most common shape of an OWC consists of a partly submerged chamber, fixed or floating, and open below the water surface in which air oscillates above the water-free surface. A duct housing an air turbine connects the chamber to the outer atmosphere. As the water level rises, the air entrapped within the chamber is compressed, producing a high-speed airflow to activate the turbine that drives an electrical generator.

OWCs present several advantages over other WECs. Principally, the minimal number of moving parts (i.e., air turbine and electrical generator) are located above the free water surface in a typical OWC system [18]. Also, OWCs can operate efficiently even when subjected to a low-frequency motion, typically around 0.1 Hz [19]. In addition, these devices attain the highest Power-Take-Off (PTO) rotational speeds, implying the lowest torques and stresses compared to other WECs. Another advantage of OWCs is the capability to control or dissipate the excess energy available to the PTO system by limiting the air turbine torque by controlling a bypass air valve or a valve in series with the air turbine [20, 21]. Furthermore, the spring-like effect of air compressibility in the chamber [22] reduces structural stresses and improves fatigue life [20].

On the other hand, the biggest drawback of OWCs is their structural cost, which is relatively high and results in an increased LCOE. This cost also increases from nearshore locations to areas of deep water and from areas of mild wave conditions to locations of extreme waves. However, there is no clear path towards commercialization within the ocean energy sector. An additional challenge is that the industry is running out of suitable locations and space due to a lack of available nearshore sites in heavily contested coastal zones, increasing conflict with other usage. The present manuscript aims to investigate the existing developments in the oscillating water column technology in the open sea by presenting the evolution of the floating OWC concept and providing an overview of current knowledge. Although numerous studies have covered different techniques to capture the ocean waves focusing on OWCs [18, 23-26], dedicated research on floating OWCs in the open sea (where severe climate conditions prevail) has not been presented to the author’s knowledge.

The rest of the paper is arranged as follows. Section 2 presents the worldwide commercial prototypes concerning the floating oscillating water column technology. Section 3 summarizes the current technology developments for the OWC and achievements, whereas Section 4 concludes the future application of wave energy. Finally, Section 5 presents the major outcomes of the present work.

2. Commercialized Prototypes

Yoshio Masuda may be regarded as the father of modern oscillating water column technology. He developed two concept buoys (a fairway and a weather buoy) powered by wave energy and equipped with an air turbine. These buoys were commercialized in Japan since 1965 and are available today from the Ryokuseisha company of Japan [27, 28]. Masuda, in 1976, promoted a commercial-size OWC device known as Kaimei (see Figure 4a), which was deployed in the sea in 1978 and operated for almost three years. The device was a barge that measured 80 m in length, 12 m in breadth, and 5.5 m in height and housed several OWCs. Initially, it included 22 pairs of OWC chambers, three featuring air turbines. During the second test campaign, Kaimei had 13 chambers, five equipped with air turbines, each with a nominal 125 kW rating. The device was moored with four slack chain lines in the front and one slack rear line and was grid-connected to the shore for power transfer. Several PTO units were tested, including Wells-type and McCormick turbines and more conventional systems with rectification valves [16, 28-31].

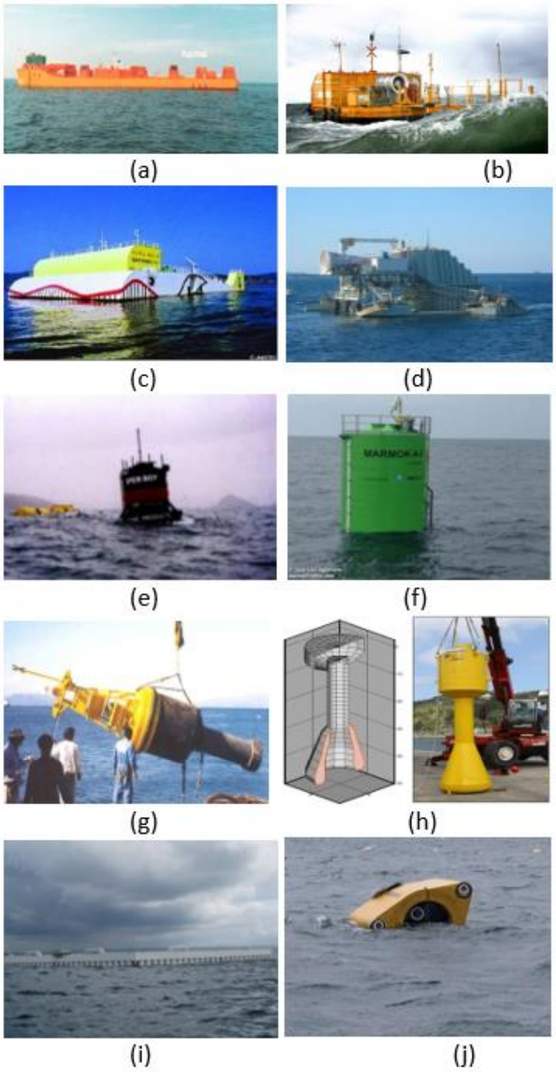

(a) (b) (c) (d) (e) (f) (g) (h) (i) (j)

Figure 4 Oscillating Water Column prototypes: (a) Kaimei wave energy conversion device (adopted from Ref. [28]); (b) OE Buoy (adopted from Ref. [32]); (c) Mighty Whale (adopted from Ref. [33]); (d) Oceanlinx Mk1 (adopted from Ref. [34]); (e) SPERBOY (adopted from Ref. [35]); (f) MARMOK-A-5 (adopted from Ref. [34]); (g) Wave Activated Generator (adopted from Ref. [36]); (h) OWC Spar buoy cross-section and 1:16th-scale model (adopted from Ref. [31]); (i) LEANCON wave energy device (adopted from Ref. [37]); (j) SEWEC wave energy device (adopted from Ref. [38]).

The power efficiency of the already developed technologies was considerably less than expected, prompting the need for different designs of power systems. The Backward bent-duct Buoy (BBDB) is a WEC type that operates on the same principle as the OWC. Yoshio Masuda introduced it in 1986 to improve the energy absorption efficiency of the existing OWCs. The device consists of an L-shaped duct, an air chamber, and a PTO system (i.e., air turbine and generator).

Since there is no central vertical chamber, the converter can operate also in shallow waters. It is worth mentioning that the opening duct initially faced the incoming wave. However, it was found that a better performance could be attained by placing the device with its back facing the wave train propagation [31].

Since its proposal, various countries have studied the BBDB, which has been used to power several navigation buoys. The OE Buoy [32], a 1:4th scale BBDB OWC, was tested in Galway Bay, Ireland, between 2007-2009 and 2011 (see Figure 4b). It was initially equipped with a Wells-type air turbine and later with an axial-flow self-rectifying impulse turbine. The device underwent various wave conditions, including severe storms with a 25-30 m/s wind speed and a wave height of 8.2 m [28]. Since then, Ocean Energy has developed several BBDB prototypes, the latest one being the OE35, demonstrated under the framework of an EU Horizon Europe Programme entitled WEDUSEA [39].

The Mighty Whale was a three-chamber OWC device developed by the Japan Marine Science and Technology Center in 1998 (see Figure 4c). The device, which encompassed a floater with dimensions 50 m in length, 30 m in width, and 12 m in height, included two turbines with a rated power of 30 kW and one turbine with a rated power of 10 kW or 50 kW, depending on the wave conditions at the installation location. The device was deployed near the mouth of Gokasho Bay and operated from 1998 to 2000, when the tests terminated. The device was removed from the sea environment in 2002 [33].

Oceanlinx was established in 1997 and specializes in the research and development of ocean-based renewable energy technology. The company has deployed Oceanlinx Mk1, a full-scale prototype with an installed capacity of 0.5 MW, at Port Kembla (see Figure 4d). The approximately 500-ton device used a parabolic wall to concentrate the wave energy in its 100 m2 square meter oscillating water chamber [34]. Its operation started in 2005 and ended in 2009. After the construction of the Mk1 device, those of Mk2 and Mk3 followed in the years 2007 and 2010. These were 1:3 scale demonstrators of 1.5 MW and 2.5 MW rated capacity units, respectively. Unfortunately, the company went bankrupt in April 2014.

SPERBOY was a floating WEC based on the OWC principle, developed, and patented by Embley Energy [35]. In 1999-2001, a 1:5 scale demonstrator was deployed at sea (see Figure 4e), which proved the design concept of the product. The literature has not reported any progress since then, and the current development stage of the device remains unknown.

MARMOK-A-5 is an offshore electrical power generator based on the oscillating water column principle with a nominal power of 30 kW (see Figure 4f). It is a floating spar-type floater of 5 m diameter and 42 m length (6 m above and 36 m below the free water surface), with a displacement of 162 Tm. The device was initially deployed in the Bay of Biscay in 2016 and operated successfully, withstanding three winters in the open waters of the Atlantic Ocean until 2018. Its mooring system was based on polymer anchor lines attached at a water depth of 90 m, whereas two Wells-type air turbines were installed at the oscillating chamber. In its second deployment (2018-2019), the device served as a test platform for various configurations, i.e., bi-radial turbine, elastomeric mooring systems, and control mechanism [34].

Wave Activated Generator (WAG) is a floating buoy (see Figure 4g) that converts the wave motion into electric power to charge batteries maintained on the buoy with two different voltage ratings, i.e., 12 V and 24 V. The converter uses the OWC technology with a maximum output of 100 W. The overall converter's height ranged between 5.7-13.3 m, diameter from 1.5-3.0 m, and total weight from 1.7-11.2 t across five different geometries [36]. Some commercially available buoys use these floaters to power navigation aids.

The OWC Spar buoy is an axisymmetric device consisting of a submerged vertical tail tube fixed to a floater that moves essentially in a heave direction. The airflow, displaced by the motion of the OWC inner free surface relative to the buoy, drives an air turbine at the top of the oscillating chamber [38]. This type of converter has been considered since the early pioneers of wave energy conversion and has been the object of numerous studies and analyses, i.e., [3, 40-43] to name a few. Figure 4h shows a picture of the prototype [31] tested at a 1:16 scale model.

LEANCON wave energy device is a multi-absorbing wave energy converter formed by a floating V-shaped slender structure, with two arms oblique 40 deg concerning the incident wavefront (see Figure 4i). The floating beams are equipped with two rows of cylindrical OWC chambers. The wave pressurizes the chamber air, forcing it through a high-pressure duct to a turbine [44]. A 1:10 scale prototype was constructed and launched in the sea in July 2015. Each arm had a length of 16.4 m and a weight of 3 tn. The converter remained in the sea until December 2015, when it was brought onshore [37]. Today, a full-scale prototype with a width of 240 m is constructed with an installed capacity of 4.6 MW.

The SEWEC device uses an internal oscillating water column to drive an air turbine and generate renewable energy. The converter has a unique feature where the OWC and all moving parts are sealed off from the ocean environment (Figure 4j). In 2015, a 1:50 scale model was tested at the University of Michigan's wave test tank, and in 2016, a 1:20 scale model was constructed, initiating sea trials [38, 45].

Apart from the floating OWCs (down- or full-scaled) tested in actual sea conditions, several converters have already reached a mature technology readiness level (TRL) validated in lab conditions. Indicative examples are the Offshore Wave Energy Ltd, the KNSwing, the SDK wave turbine, and the MRC1000 OWC.

The Offshore Wave Energy Ltd (OWEL) wave energy converter is a floating rectangular device open at one end to capture the incoming wave field (see Figure 5a). The mooring system of the converter considers wind and tides to ensure the presentation of this open end to the incoming waves. The waves repeatedly compress the air trapped within the ducts, directing it to drive an air turbine that generates electricity. An OWEL demonstrator of 350 kW was constructed under UK Research and Innovation's funding [46, 47] to operate in early 2013. However, to the author's knowledge, there have yet to be any further reports on a full-scale prototype.

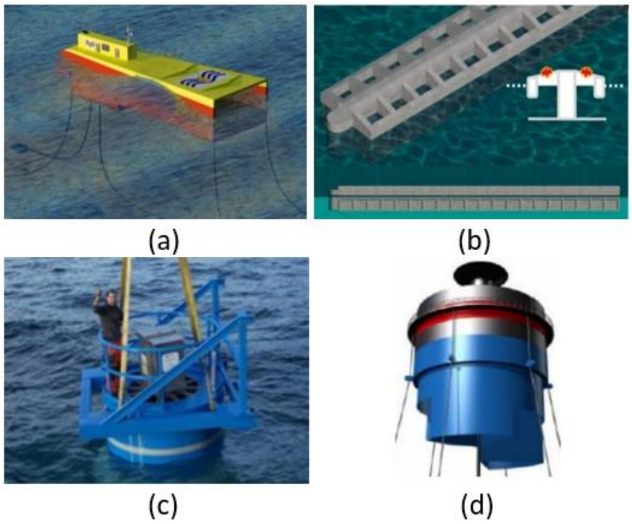


Figure 5 Oscillating Water Column prototypes that are in a design process: (a) OWEL wave energy converter (adopted from Ref. [47]); (b) KNSwing floating WEC (adopted from Ref. [48]); (c) SDK Wave turbine (adopted from Ref. [49]), (d) MRC1000 floating buoy (adopted from Ref. [50]).

The KNSwing device is a floating multi-chambered attenuator OWC (Figure 5b). The large ship-like structure provides a stable frame for the OWC chambers that hardly move in all normal sea state conditions. The WEC is moored at the bow of the structure using a turret mooring system, whereas an additional optional mooring line can be attached to the stern for safety reasons. In 2015, a 3 m long-scaled model was constructed, which included 40 OWC chambers, each damped by an orifice with a diameter of 14 mm [48, 51].

SENDEKIA has invented and patented a conversion system consisting of a water turbine working under the OWC principle. The system encompasses an oscillating water column chamber, open at its bottom to the sea, and a wave turbine (SDK Wave turbine). The turbine can take off power from hydraulic bidirectional oscillating movement. Due to its blade pitch variation, the turbine constantly rotates in the same direction regardless of the direction of the flow. In 2013, a 1:20 scale model was tested in the Ifremer wave basin in Brest, France, whereas a larger model (i.e., 1:5 scale, see Figure 5c) will be installed in Cartagena Harbor soon [49].

The MRC1000 is a floating converter that also uses the OWC technology. The device consists of six oscillating columns, each tuned to different frequencies for amplified wave energy absorption (Figure 5d). During its development, three different PTO systems were examined. Initially, the oscillating air drove an impulse turbine, whereas in the second stage, the turbine drove a hydraulic circuit. At its final design stage, the high-pressure oil drives an electric generator [52]. Various small-scale trials have been performed to efficiently construct a full-scale prototype of 1 MW [50].

3. Literature Review

3.1 OWC Geometrical Characteristics

Many publications of past and ongoing studies into floating oscillating water column devices reveal the preference for this wave energy conversion methodology due to the OWC's simple operation, structural robustness, ease of maintenance, and versatility. The OWC converter harnesses the energy of a wave by using water-free surface movement as a piston and, therefore, effectively creating an air volume flow that drives an air turbine coupled to a generator. The discussion below focuses on the structural characteristics of different types of OWCs.

3.1.1 Cylindrical Oscillating Chamber

The first known hydrodynamic analysis of a floating OWC was applied by McCormick [53], who developed a theoretical analysis of a pneumatic-type wave energy conversion buoy assuming independence of the buoy heave motion and the motion of the water column within the oscillating chamber. The numerical method developed in [54] assumed that the OWC converter consisted of two bodies: the floating device and the horizontal rigid thin body with zero mass representing the internal free water surface. In [55], the authors presented a general formulation of the hydromechanical problem of a floating cylindrical OWC and solved the corresponding boundary-value problem using the macroelement technique. The method used the idealization of the flow around and inside the converter through macroelements of rectangular shape for cross-sections and co-axial rings for vertical bodies of resolution. Falnes [56] thoroughly considered the interactions between waves and OWC devices in linear potential theory. This work is cited as one of the most complete compilations of mathematical work related to the absorption of waves by oscillating bodies. Hong et al. [57] presented a numerical estimation of the hydrodynamic properties of a floating OWC device within the scope of linear theory. They also evaluated the time mean drift forces on the converter by applying the near-field method for several values of PTO characteristics. Mavrakos and Konispoliatis [58, 59] examined two types of floating OWC devices. The first one [58] consisted of a vertical cylindrical oscillating chamber with finite wall thickness.

In contrast, the second one [59] consisted of two concentric vertical circular cylinders with differentiations in geometry (wall thickness, draught, shape of chamber, and turbine characteristics). In order to evaluate the velocity potential of the flow field around the device, the study investigated three types of first-order boundary value problems: the diffraction problem, the radiation problem resulting from the forced oscillations of the body in otherwise still water, and the radiation problem resulting from an oscillating pressure head acting on the inner free surface of the OWC.

Stappenbelt and Cooper [60] investigated analytically the maximum power capture of a floating OWC converter in the heave direction by introducing a floating system mechanical oscillator model. They concluded that two resonant peaks were evident, i.e., the first corresponded to the pumping resonance, whereas the second was to the structure's natural frequency. The power capture was low when the pumping and structure resonant frequencies coincided.

On the other hand, separating these frequencies resulted in a significant increase in maximum power capture. These two resonant frequencies, i.e., the converter's natural frequency and the chamber's pumping frequency, were also examined in [61]. The study specifically developed a two-dimensional, fully nonlinear CFD model with a dynamic mesh to analyze the performance of a heave-only floating OWC. The conclusion was that the converter's efficiency could be adjusted by manipulating the air turbine's damping and mooring elasticity coefficients. In [62, 63], the authors used linear potential flow theory to examine the resonant frequencies of a floating OWC. They derived that the natural pumping frequency remained unaffected by the air pressure inside the chamber, whereas the opposite held for the natural frequency of the converter. In [64], the authors developed a CFD model to describe the interactions between regular waves and an OWC, assuming incompressible fluid and viscous flow. The results were compared with an analytical approach assuming a compressible air flow. The comparisons showed that although slight differences were attained for the water surface elevation inside the chamber, a 30% relative error was experienced in the airflow velocity. Sheng & Lewis [65] investigated the effect of air compressibility in the chamber of an OWC on its power conversion. They concluded that the dynamic responses of the converter were strongly dependent on the air compressibility.

In [66], the authors presented a holistic analytical model of an OWC, including turbine control, for efficient wave energy absorption in the Mediterranean Sea. The analysis considered two types of air turbines, the Wells type, and the axial impulse turbine, and calculated the anticipated annual energy harvesting. A small-scale WEC device for battery charging was examined in [67]. Here, the WEC buoy was mounting an OWC or a heaving buoy. The authors concluded that the OWC was inadequate compared to the heaving buoy. Furthermore, a hybrid solar and heaving absorbers system could form the optimum option for annual power supply. In [68], the authors examined the effect of bathymetry on the efficiency of a floating cylindrical OWC under irregular wave impact. Here, CFD methodologies were applied, concluding that the channel's bathymetry did not significantly influence the irregular wave propagation.

Laboratory experiments on an axisymmetric floating OWC were reported in [69]. In this study, a two-degree-of-freedom system with an applied damping mechanism was considered. In [70], the experiment investigated the hydrodynamic performance of a moored cylindrical OWC. The outcomes were compared with a second-order time domain Higher-Order Boundary Element method. The latter was applied to simulate the nonlinear wave-body interactions. The proper selection of mooring stiffness was found to increase the effective frequency bandwidth.

3.1.2 Spar-Type OWC

A particular case of a floating cylindrical oscillating water column device is the Spar buoy OWC converter was patented by Falcao et al. [71] in 2020. The device's geometry was optimized in [72, 73], considering the air compressibility effect inside the chamber and a linear characteristic curve of the Wells-type air turbine. Henriques et al. [74, 75] extended this analysis by optimizing the hydrodynamic shape of the buoy, the characteristics of the turbine and the generator, and the control law of the generator's electromagnetic torque. The carried-out analysis revealed the ability of the self-powered sensor Spar buoy to provide the required annual-averaged power output for the climate conditions of the western coast of Portugal. Experimental measurements also verified the device's integrity on 1:32 scale models [76]. Here, the OWC Spar buoy's performance and mooring system were compared for an isolated configuration and a three-device triangular array. The array configuration appears beneficial for wave climates characterized by large energy periods. Towards the increase of the Spar buoy's efficiency, Gomes et al. [77] examined whether placing the converter in a wave channel would increase its wave absorption ability. Here, the channel side walls were numerically simulated by a periodic array of devices and, alternatively, by two finite-length walls. The numerical simulations showed that the presence of the walls can amplify the power captured by the device up to 15% and 10% for regular and irregular wave trains, respectively. In addition, in [41], parametric resonance, a nonlinear phenomenon that induces large roll and pitch motions, was examined in the Spar buoy. Experiments were carried out for a 1:32 scale model, and the numerical results were verified. The analysis concluded that parametric resonance negatively impacted power extraction efficiency by up to 53%. Gradowski et al. [78] recently conducted a geometric analysis on the Spar buoy converter, assuming an enlarged inner tube. From their analysis, it derived that as the inner tube diameter increased, the energy extraction also increased by up to 6.7%, and the mass of the converter was reduced by up to 11.4%, which could effectively decrease the cost of the converter. In [79], the authors examined a modified Spar buoy OWC. Here, the bottom of the converter was not filled with a ballast material, but a thick ring was located at the lower end of the tube. The experimental results introduced nonlinear effects caused by viscous flow and turbine damping under regular and irregular wave trains for a 1:10 scale model.

The literature has thoroughly examined another floating spar-type device, apart from the Spar buoy OWC converter. The Tupperwave device (see Figure 6a) [80] is a closed-circuit spar-type OWC, which uses non-return valves and two accumulator chambers to create a smooth, unidirectional flow across a unidirectional turbine. The vertical motion of the internal surface alternatively compresses the air into the high-pressure chamber and decompresses the air in the low-pressure chamber. This device creates a pressure differential between the chambers connected via a unidirectional air turbine. The converter was initially described in [80, 81], whereas in [82] the Tupperwave concept was compared to a conventional OWC device with a self-rectifying turbine. It was concluded that the Tupperwave can outperform the conventional OWC by up to 20%. Furthermore, in [83], a non-isentropic numerical model was developed, which investigated the effect of the increase in air temperature in the Tupperwave converter.

In addition to the two WECs mentioned above (i.e., Spar buoy and Tupperwave), several other floating spar-type OWCs have been studied recently. In a notable study [84], the authors developed a numerical tool to predict the heave motion of the spar and the water oscillations inside the structure. They validated the results against experimental outcomes. Also, in [85], the performance efficiency and sustainability of a spar-type OWC were numerically and experimentally examined, accounting for the influence of governing thermodynamic variables, such as moisture, temperature, and pressure, in the compression/expansion polytropic process. The analysis considered gas subsystems inside and outside the converter, the net exchange balance, and the interpretation of the OWC as a thermodynamic engine.

3.1.3 Square-Type OWC

Researchers worldwide have examined numerous floating devices with a rectangular chamber cross-section area. Lee and Kim [86] determined the wave elevation inside a box-type OWC. They compared the results from a theoretical 2D analysis with experimental outcomes and found that the inner wave elevation decreased as the wave frequency increased. Gerad et al. [87] examined the behavior of an OWC at forward, central, and aft locations within a fixed vessel. Their numerical and experimental analysis concluded that additional peaks of the water surface elevation occurred at the forward and aft chamber from the vessel’s pitching motion. In [88, 89], a new elongated OWC structure (Seabreath converter -see Figure 6b) was examined by a series of aligned rectangular oscillating chambers. They conducted scaled wave tank experiments to specify the geometric characteristics of the device. The analysis evaluated that a prototype measuring 120 m in length, 24 m in width, and 20 m in height would have an expected average potential production of 850 kW. Also, a 40-chamber attenuator-type OWC device (i.e., KNSwing converter) was analyzed numerically and experimentally in [51, 90]. Potential flow-based calculations were conducted and compared well with the experiments. The study found that the ship-like converter demonstrated seaworthiness even in the largest extreme sea conditions, with a maximum capture width ratio of 30% in regular waves. This value increased to 37% for short crested waves with large directional spreading. In addition, a weakly compressible smoothed particle hydrodynamics model was developed [91] and applied to the KNSwing converter. In this scenario, the air turbine effect was simulated by applying an equivalent damping force to a thin floating plate inside the chamber. The motion of the inner water surface was then calculated based on the heaving displacement of this plate. In [92], computational and experimental results for a modified version of a single chamber from the KNSwing converter, which included a valve system allowing for one-way venting, were presented. The numerical and experimental calculations confirmed the modified design by predicting 30% more absorbed power near resonance than two-way wave energy absorption.

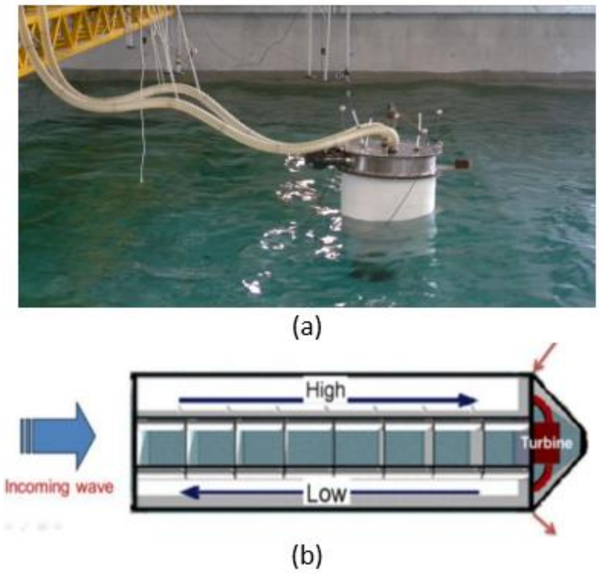


Figure 6 Spar-type and square-type oscillating water column models: (a) Tupperwave converter scaled model (adopted from Ref. [93]); (b) Schematic representation of the Seabreath WEC (adopted from Ref. [89]).

Due to the increased interest in recent years in Computational Fluid Dynamics (CFD) modeling, which solves the fluid flow problem using Navier-Stokes equations, several authors have studied the importance of including viscosity in OWC problems. Specifically, Iturrioz et al. [94] developed a CFD solver, validated with experimental data, for free surface elevation-, air pressure-, and air velocity- calculation for a box-type OWC converter. Also, in [95], the effect of the oscillating chamber's geometry (i.e., the characteristics of the front and rear lip) on the hydrodynamic performance of an offshore rectangular shape, OWC, was examined. The study concluded that by optimizing the combination of the submergence ratio and thickness of the chamber's lip, a peak efficiency exceeding 0.79 could be achieved. The improvement of the hydrodynamic performance of an asymmetrical offshore OWC was the object of [96]. The performance of a 1:36 scale OWC model was designed using a CFD model and was validated experimentally. Specifically, the design procedure involved the design and optimization of the converter's chamber and the design of the external support structure, which governed the buoyancy, stability, structural integrity, and dynamic properties of the WEC. The obtained results revealed an 81.5% increase in the capture width ratio of an OWC with optimized oscillating chamber geometry and an external support system. A CFD solver was also developed in [97] to examine the effect of the chamber's width on the energy conversion and the mechanical characteristics of an offshore OWC. Here, the study examined different array configurations of box-type OWCs with and without distance between them. The conclusion was that when there was a gap between the chambers, the OWCs demonstrated better or similar comprehensive energy conversion compared to the no-gap case.

Numerous studies in the literature have examined the backward-bent duct buoy (BBDB) wave power device (see Section 2). In [98-100], researchers presented the geometrical and hydrodynamic characteristics of the converter, while McCormick and Sheehan [101] and later Hong et al. [102] derived that the time-mean drift forces are in the reverse direction of the propagation of the incident waves, causing the buoy to drift into the waves. Experimental tests verifying this were presented in [103, 104]. Bull and Johnson [105] developed a linear performance model in the frequency domain, linking the oscillating structure to air-pressure fluctuations with a Wells-type air turbine for a floating BBDB converter to optimize its resistive damping. Furthermore, [106] developed a time-domain model for a moored BBDB. The model simulated the fully coupled WEC dynamic, the mooring lines, the structure’s hydrodynamics, the air chamber thermodynamics, and the air turbine dynamics and generator. The authors simulated 36 different sea states of a Canadian Pacific location, providing an annual power production of 530 MWh. Trivedi and Koley [107] explored the yearly-averaged potential of a BBDB in ocean wave conditions. As the incident wavelength shortened, they observed an increase in average efficiency.

Regarding the geometry of the converter, a high front wall’s draft caused a decrease in the efficiency amplitude. In contrast, a wider oscillating chamber increased the absorption efficiency. Recently, Liu et al. [108] conducted experiments in a wave flume of a scaled BBDB interacting with irregular waves. Their analysis concluded that the pitching and the heaving motions affected the captured wave power positively and negatively, respectively.

It is worth mentioning that various variations of the original BBDB device geometry, as presented by Masuda, have been considered in the literature. Bull et al. [109] presented the Reference Model 6 (RM6) BBDB converter, providing some insights on the optimization of the air turbine PTO and the electricity generation mechanism. This converter (i.e., RM6) was also studied in [110]. The study calculated the power performance curve of the WEC in irregular waves. It proposed that a uniform water column and a longer horizontal tube length could benefit the annual energy produced. In addition, an alternative proposal for wave energy absorption, based on the BBDB technology, is the forward-facing bent oscillating water column [111]. In [112, 113], the authors theoretically and experimentally studied this converter. Researchers developed a CFD model in [114] to simulate the hydrodynamic interactions between the wave trains and the converter when the latter was considered moored on the seabed.

3.1.4 OWC of a Random Geometry

Several prototype models with different operational principles from those mentioned above have been developed in recent years regarding the principle for wave energy extraction under oscillating water column technology. UGEN, a floating device with a U-tank for generating electricity from waves, was first introduced and patented by Instituto Superior Tecnico in 2010 [115]. The device comprises an asymmetric floater and a PTO system of a self-rectifying air turbine directly coupled to an electrical generator (see Figure 7a). The motion of the U-shaped OWC, mainly induced by the rolling of the floater, forces the air through the air turbine to absorb the wave energy. Researchers presented a numerical model and assessment of the converter in [116, 117], demonstrating the existence of two natural periods, i.e., the rolling and the U chamber's natural periods. The system performed better when the two natural periods were separated, especially for a period range near the rolling natural period. In addition, in [118], an optimization method for the floater's geometry was developed. The optimized geometry had larger dimensions, mass, and power extraction up to 5.9 times higher than the original. A 1:24 scale model of the converter was used to experimentally validate its performance under regular and irregular wave conditions in the study conducted in [119]. Apart from the two aforementioned natural periods, the occurrence of low-cycle auto-parametric resonance under certain wave conditions was detected. This phenomenon induced large roll motions, affecting power extraction and increasing the mooring line loads.

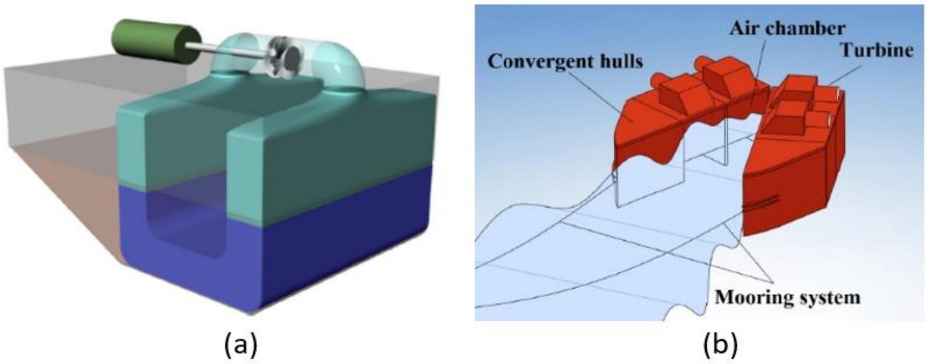


Figure 7 OWC of a random geometry: (a) 3D representation of the UGEN converter (adopted from Ref. [118]); (b) 3D representation of the MCOW converter (adopted from Ref. [120]).

Inspired by the multiple-chamber OWCs (see Section 3.2), a novel 3D multi-chamber OWC wave energy converter (MCOW) has been proposed [120]. It consists of two hulls of an equal number of installed OWCs, which are converging at the stern, thereby forming a wedge in the plan view that allows the angle between the hulls to be varied in the range of 0-120 deg (see Figure 7b). The device is moored to a catenary buoy using a single-point mooring system that allows the hulls' opening angle to face the incident wave. The study [120] dealt with the experimental verification of the proposed concept using a 1:30 scale model. The study investigated the effects of wave amplitude and the geometrical characteristics of the converter on its hydrodynamic performance. The conclusion was that the converter's hydrodynamic efficiency increased as the draught and the wave amplitude decreased.

In contrast, the efficiency comparison of the two chambers revealed that the rear chamber had lower efficiency than the front one, which should be carefully considered during system design. Other recent studies in OWC's geometry optimization are [121, 122], which dealt with a toroidal converter and a rectangular OWC with an elliptical front wall. Specifically, in [121], Galerkin's method was applied to solve the corresponding diffraction and radiation problems in the frequency domain. The analysis concluded that a toroidal OWC with a cylindrical oscillating chamber attained an increased wave power efficiency compared to the toroidal converter with a toroidal chamber. The study in [122] applied a 2D numerical simulation method to evaluate the inner air pressure variation and outlet airflow of an OWC with various elliptical wall geometric characteristics. The elliptical front wall improved the energy conversion effect by up to 25% compared to the efficiency of an OWC with a rectangular wall.

3.2 Classes of OWCs

Regarding the different types of OWCs, several classes of converters have been presented in the literature. These can be categorized as follows:

3.2.1 Breakwater-Type OWC

Fixed and floating breakwaters are typically considered the most suitable maritime structures for WEC integration. In addition, floating breakwaters have the primary operational function of wave attenuation to provide shore environmental protection. A floating breakwater embedding an OWC in its middle section was experimentally and numerically studied in [123] and [124]. The analyses concluded that maximizing the heave motions of the breakwater is essential for achieving optimal power efficiency. The opposite held for the sway motions of the breakwater. In [125, 126], they examined an integrated OWC-breakwater system and concluded that there was increased wave transmission and motion response performance with a proper selection of the OWC chamber geometry. A floating breakwater integrated with OWC converters was also studied in [127] (see Figure 8a). This study explored how the device configuration, the breakwater's width, the pneumatic damping, and the structure's motions influenced the performance of the converters. Integrating multiple devices on the breakwater was concluded to improve mean capture width relative to a single integrated device. Careful consideration of device spacing and pneumatic damping characteristics is essential in the design phase. An optimum selection of these parameters can lead to an absorption of 80% of the available wave energy, which interacts with the breakwater. Subsequently, the study [127] was extended to [128], covering the impact of the OWCs on the floating breakwater's wave attenuation and motion characteristics. The study found that pitch motion had the most detrimental effect on OWC efficiency, and the integration of OWC had a beneficial impact on wave attenuation and breakwater motions. The study [129] aimed to provide further evidence to support the feasibility of the OWC-integrated floating breakwater. It analyzed the performance of energy extraction, wave attenuation, and motions in irregular waves. The analysis concluded that the OWCs' performance in irregular waves was equivalent to that observed in regular waves. Furthermore, breakwater motions in irregular waves benefitted from the OWC integration with observed reductions in heave and pitch magnitudes. The same held for regular wave trains. The study in [130] presented an experimental analysis of multiple OWCs integrated on a very large free-floating structure (VLFS) to investigate the pneumatic conversion efficiency of the structure. A remarkable mitigation of the structure's heave motion due to the presence of the embedded OWCs was found, particularly for longer incident waves. An extension of [130] was presented in [131], in which a laboratory-scale physical model was tested in a wave-current flume to examine the pneumatic conversion efficiency of multiple OWCs installed on VLFS in both fixed and floating conditions. The analysis proved that the integration of OWC in VLFS increased pneumatic conversion efficiency by up to 46% in specific irregular wave spectra for the floating condition. Zhao et al. [132] examined the hydrodynamic performance of a floating OWC-breakwater system with single--, dual--, and triple-chamber arrangements via experiments. It was shown that a triple-chamber OWC attained higher power extraction performance than that of a single-chamber OWC. In addition, the wave attenuation performance was higher, and the dissipation coefficient was relatively smaller for a triple-chamber OWC than that of a single-chamber OWC. A floating box-type breakwater with dual pneumatic chambers was experimentally studied in [133] to examine the effect of the wave period, chambers' draft, water depth, and chambers' arrangements on the power extraction efficiency. It was derived that the front chamber always played the main role in power absorption. Hence, its geometry and, consequently, its natural period should be designed based on the dominating period of the wave spectrum. On the other hand, the rear chamber was only a supplement, and its natural period should be designed against longer waves. Deng et al. [134] investigated numerically and experimentally the hydrodynamic characteristics of a novel oscillating water column breakwater encompassing a horizontal bottom plate. It was concluded that an appropriate length selection of the horizontal bottom plate could effectively improve energy dissipation. The optimal length D was found in the range of $2 \leq D/B \leq 2.5$, where B was the OWC chamber's breadth. Recently, Cheng et al. [135] proposed an innovative breakwater solution encompassing an oscillating buoy converter inside the chamber of an OWC. A numerical investigation was conducted on this configuration, and the results were compared with those of an isolated breakwater and an OWC-integrated breakwater system. The study demonstrated that the proposed solution benefited both wave energy conversion and transmitted wave attenuation. Also, Cheng et al. [136] compared experimentally and numerically the hydrodynamic performance of an OWC-type dual pontoon- and an oscillating buoy-type single pontoon floating breakwater. Here, the displacements and the total pontoon widths were kept the same for the two hybrid systems. In contrast, the PTO systems for the two models were modeled by an aerodynamic damper for the oscillating buoy and a circular orifice for the OWC, respectively. The presented comparisons found that the wave attenuation and energy conversion of the OWC-type breakwater with a non-uniform chamber draft were better than those of the oscillating buoy. Nevertheless, although under the premise of the same pontoon draft, the maximum conversion efficiency of the OWC was higher than that of the oscillating body, the effective frequency bandwidth was almost the same between the two devices. Additionally, a double-body floating breakwater that combined an OWC with a perforated floating box was examined in [137] (see Figure 8b). The converter was embedded within the floating box facing the incoming waves, whereas the perforated structure was incorporated into the floating box on the opposite side facing the back wave. The numerical simulations concluded that the wave dissipation effect was superior to that of similar structures. In contrast, the width of the OWC opening and the water depth greatly influenced the wave dissipation performance of the structure. Specifically, it was derived that a wider opening was more effective for long-period waves, and a shallow water depth yielded better wave dissipation.

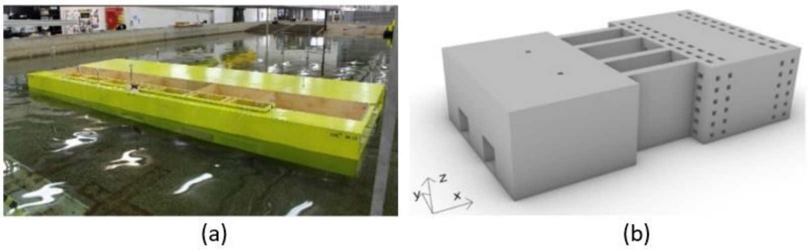


Figure 8 Breakwater with integrated OWC devices: (a) Scaled-down breakwater in the test basin of Australian Maritime College (adopted from Ref. [127]); (b) Visual representation of a perforated floating breakwater (adopted from Ref. [137]).

3.2.2 Breakwater & OWC Converters

In addition to breakwater-integrated wave energy converters, OWCs located at a distance from breakwaters have also been considered in the literature. Specifically, breakwaters and oscillating water column converters have been primarily combined with large floating structures to reduce the latter structural deflections. Hong et al. [138] considered a freely floating forward-facing bent oscillating water column placed in front of a very large free-floating structure (VLFS) of infinite breadth. A solution method for the velocity potential boundary-value problem was developed by applying a Green integral equation with a Kelvin-type Green function in a finite depth water. The researchers concluded that the presence of the OWC in front of the VLFS significantly reduced the latter's vertical displacements. Subsequently, in [139], those above forward-facing bent OWC were connected by a pin with the VLFS. In this case, the researchers coupled the Bernoulli-Euler beam equation for the structure with the OWC's motion equations. The presence of the pin-connected OWC reduced the deflections, bending moments, and shear forces of the VLFS in waves. The feasibility of integrating a VLFS with multiple wave energy converters, combining OWCs and oscillating flaps (OF), was examined in [140]. This study applied a time-domain numerical problem based on the modal expansion theory and the nonlinear potential flow theory to optimize the size and layout of an array of OWCs and OF placed in front of a VLFS. Compared to a single OWC and OF, higher energy conversion was achieved due to the beneficial wave interaction phenomena, reducing the hydroelastic response of the VLFS. The amplification increased further as the distance between the OWC and the structure increased. Regarding the chamber's width, the energy conversion efficiency decreased with chamber width in short-period waves and vice versa in long-period waves.

Recently, the amplified incoming wave energy in front of a breakwater, due to the scattered and reflected waves originating from the presence of the vertical wall, has triggered increased interest in wave energy conversion systems operating near a breakwater. Konispoliatis and Mavrakos [141] investigated the efficiency of a floating OWC placed in front of a reflecting vertical wall. Here, the method of images was applied to simulate the hydrodynamic interactions between the float and the adjacent breakwater. According to the method, the problem under investigation was equivalent to an array of two OWCs consisting of the initial and its image virtual converter concerning the vertical wall exposed to the action of surface waves without the presence of the breakwater. The conclusion was that the amplified wave interaction phenomena between the array members (i.e., OWC and vertical wall) were not always constructive for the converter’s power efficiency compared to an isolated OWC.

Nevertheless, the power performance could be improved by appropriately selecting the distance between the device and the breakwater. The authors proposed in [142] a novel WEC-breakwater system composed of a heaving OWC device and a stationary breakwater . In this study, the authors solved the corresponding scattered and radiation problems within the realm of potential flow theory. They discovered that optimizing the distance between the converter and the vertical wall against the wavelength maximized power extraction by the converter, satisfying the sloshing mode inside the water gap. Ram et al. [143] examined numerically the effect of the wave period, the distance between the OWC and the breakwater, and the breakwater size on the performance of a floating OWC placed in front of a vertical wall. The numerical results showed optimal performance for the highest examined wave frequency (i.e., 4.833 rad/s).

In contrast, a narrow distance between the converter and the wall and a small breakwater size demonstrated favorable results. Other relevant studies towards more efficient OWC-breakwater configurations concern an OWC device coupled with a parabolic breakwater [144, 145] and an OWC converter placed in front of a V-shaped vertical wall [146]. Both studies observed a remarkable wave elevation and power capture efficiency, which increased as the breakwater’s formed angle decreased.

3.2.3 Multiple Chamber-Type OWC

To expand the wave-frequency bandwidth and enhance power efficiency, researchers have proposed the concept of multiple-chamber converters implemented in a floating oscillating water column device. Initially, researchers explored the potential integration of oscillating water columns with multiple chambers on floating breakwaters ([126, 133]). In addition, Shalby et al. [147] developed a numerical model in the time domain, which was also verified experimentally for estimating multi-chamber OWC responses. The model combined hydrodynamic and thermodynamic system equations of a rigid piston in the linear potential wave theory framework. In [148], researchers numerically investigated the hydrodynamic performance of a 2D dual oscillating water column (OWC) system with a gap. The system comprised two offshore heaving OWCs and an onshore unit, utilizing computational fluid dynamics (CFD) methodologies. The objective was to enhance wave power performance and dissipate reflected wave energy. The analysis concluded that maintaining a small draft of the front oscillating water column's back lip and employing a high spring stiffness was more advisable for achieving high performance in the entire system.

Subsequently, Xu et al. [149] conducted a series of tests on a 1:50 scale model of a dual chamber OWC moored by three flexible mooring systems in regular and irregular waves. The mooring systems included one modified catenary anchor leg mooring concept and two compact mooring systems. The results showed that the catenary anchor system was the preferable mooring option for energy absorption in small wave heights. On the other hand, the power performance of the converter was improved in large wave heights when moored by a compact mooring system. Furthermore, the study demonstrated that mooring tensions exhibited significant nonlinearities, especially when synthetic fiber ropes were used.

In contrast, the opposite held for the fatigue damage of a chain mooring since it was greater than that of synthetic lines. The study [149] was extended in [150], focusing on the motion characteristics of the dual chamber OWC and their effect on the free surface elevations and air pressure inside the oscillating chambers (see Figure 9a). In surge motion, the system's natural frequency was much lower than the generated waves, while in some cases, the device followed the incident wave motion due to opposing drift forces. Also, the amplitude of the free surface elevation inside the chambers was amplified up to 2 times the incident wave height, increasing the overall power performance of the system. A novel floating dual-chamber OWC converter, consisting of a fore chamber facing up directly to the incident wave train and an actual chamber with indirect interactions with the propagating waves, was theoretically, numerically, and experimentally studied in [151, 152]. The study revealed that the device could convert all the energy of the incoming waves to pneumatic power under specific wave conditions, a phenomenon rarely detected in other types of WECs. Precisely, for the Portuguese oceanic area, the average efficiency of the device was estimated to be over 55% and 41% for regular and random waves. Recently, Portillo et al. [153, 154] focused on the coaxial-duct OWC converter. This new floating OWC concept consists of two coaxial cylindrical ducts interconnected at their bottom ends (see Figure 9b). The outer duct is open to the sea at its top, while the inner duct extends above the sea level and connects to a self-rectifying air turbine. The experiments conducted on a 1:40 scale model in regular and irregular waves and various damping conditions concluded that compressibility effects had constructive and destructive effects on the mean absorbed power at specific wave frequencies. The relative magnitude of positive to negative (or harmful to positive) compressibility effects between transition regions was separated by critical points, categorized as *Equicompressum Nullum* and *Equicompessum*. Knowledge of these critical points could bring important implications for the control of the OWCs.

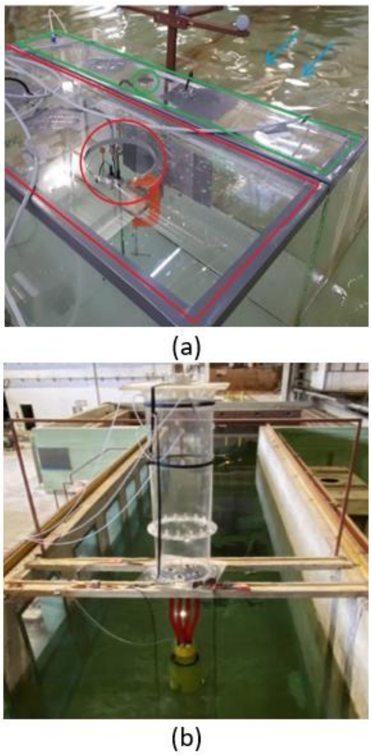


Figure 9 Dual chamber OWC devices: (a) Scaled-down model of two chambers (the rear chamber is in red, and the front in green. Blue arrows indicate the wave train direction) (adapted from Ref. [150]); (b) Scaled-down coaxial-duct OWC converter (adapted from Ref. [153]).

3.2.4 OWC Array

The main difference between a floating isolated oscillating water column device and an array of such converters is the wave interaction phenomena between the array's members. These wave interactions are not always beneficial for wave energy absorption, which has been the subject of many studies. As early as the 1980s, Falnes & McIver [155] applied a mathematical description, based on linear theory, for a system of OWCs. The study demonstrated that all the incident wave power can be captured with optimum oscillation amplitudes. In [156, 157], researchers examined various interacting free-floating OWC devices floating independently or as a unit. An analytical solution method for three boundary value problems, namely the diffraction, the motion- and the pressure-radiation problems, was given using the multiple scattering approach. The analysis focused on a vertical cylindrical OWC chamber with or without a coaxial solid vertical cylinder. The conclusion was that the array spacing can significantly affect the total power output, especially when the inter-body distance in the array is close to the wavelength. In [158], the study examined the effect of inter-body spacing on the eigenfrequencies of an OWC array in an equilateral triangle. The findings indicated that the maximum power absorption might occur at a specific distance where the damping of the dominant eigenmode is less than that of a single converter. The study in [159] developed a numerical methodology for evaluating linear and nonlinear wave forces, motion responses, and wave power absorption in an array of floating OWCs with an arbitrary shape. In this case, the OWC geometry was optimized by either attaching an arc-shaped reflector to the rear bottom of the converter or by placing the device on a submerged caisson. Observations revealed a series of significant peaks associated with wave energy harvesting. These peaks were linked to the resonant motion of the entrapped fluid and the resonant frequencies of rigid-body motions.

In [160, 161], researchers examined two commercialized OWC prototypes, the MARMOK-A-5 and the OWC Spar buoy, within an array of converters. In [160], researchers developed a state-space model for simulating an array of OWCs with nonlinear power take-off dynamics. The simulation results demonstrated that incorporating an OWC in an array and thus considering wave interactions can broaden the effective range of desirable regular wave frequencies for energy conversion. Additionally, the cross-body interactions were deemed negligible in irregular waves at specific distances between the array members. In [161], a numerical analysis of a triangular array of Spar buoy OWCs, with bottom and inter-body mooring connections, was presented under regular and irregular wave train interactions. A coupling effect between surge/sway and heave motions was observed for regular waves, whereas the converters' average heave amplitude decreased by 6.8%. Furthermore, the simulations with a set of uni-directional irregular wave trains showed that an angle of 30 deg of the incoming wave provided better results for the examined mooring configurations.

3.2.5 Hybrid OWC Systems

One promising alternative to reduce the cost and increase the performance of renewable energy technologies is the application of hybrid systems that combine offshore wind turbines (WT) with OWCs converters and/or wave energy converters of different operation principles into one hub. Even though these hybrid systems are still in the early stages of application and far from commercial use, several studies have reported on integrating oscillating water column devices onto floating wind turbines in the marine sector. Aubault et al. [162] proposed a floating structure for multi-megawatt WT combined with an OWC. The structure was a three-column semi-submersible platform encompassing an OWC converter at one of the floater columns (see Figure 10a). They developed a numerical model, validated experimentally, to account for the coupling effect between the OWC PTO and the platform's motions. The study demonstrated that the influence of the oscillating air pressure in the chamber on the platform's responses was limited, resulting in a slight increase in pitch and roll motions. [163] presented a tension leg platform featuring three hydrodynamically interacting OWCs and a 5 MW WT. A coupled-hydro-aero-elastic formulation was developed in the frequency and time domain, considering the floater's hydrodynamics and the WT's aerodynamic loads. The analysis concluded that the chamber air pressure head had little influence on the structure's surge motions. On the contrary, tension forces along the mooring tendons greatly depended on the air pressure variation. The work was extended in [164], which involved numerical validations with corresponding scaled-down tank tests to extrapolate the effect of the air pressure inside the OWCs on the platform's seakeeping. Hence, a 1:40 scaled-down model with different orifice diameters at the top of each chamber was considered (see Figure 10b). Also, the steady (aerodynamic) thrust was specified using small thrusters mounted at the level of the WT nacelle. The study demonstrated that the inner pressure and tension of the mooring lines decreased with increased orifice diameter. In contrast, the orifice diameter did not affect the surge motions of the structure. Sarmiento et al. [165] presented experimental ocean basin tests of a multi-use platform (MUP), which was moored with conventional mooring lines and encompassed three OWCs and a 5 MW WT (see Figure 10c). In this setup, the wind effect was simulated using a portable wind generator, and the wind turbine acted as a drag disk. In contrast, different diameter openings on each OWC chamber conceptualized the OWC air turbines. The experiments provided evidence that varying wind velocities did not impact the dynamics of the chambers. In addition, the existence of the WT introduced higher motions and mooring systems loads, whereas the OWC effect was limited. Konispoliatis et al. [166, 167] studied a multi-purpose floating TLP structure named REFOS, which consisted of three OWCs converters and a 10 MW WT for the combined wind and wave energy resource exploitation. The analysis focused on the description of the environmental conditions for two locations in the Mediterranean Sea and one location in the North Sea, as well as on the hydro-servo-aero-elastic coupled modeling for various design load cases and the determination of the extreme and fatigue loads of the structure's main components. Wave tank experiments complemented the results from the analysis on a 1:60 scale model. Here, perforated carpets simulated the air turbines' PTO at the top of the chambers. In contrast, only the steady aerodynamic thrust was considered, applying a pulling force through a horizontal string attached to the nacelle height at one end. In contrast, at the other end, a weight equal to the nominal wind turbine thrust load was suspended using a suitable pulley. The conclusion was that the responses of the hybrid structure did not appear to be affected by the wind velocity. On the contrary, the characteristics of the air turbine dominate the structure's motions and tension forces. The presence of the OWCs was observed to increase the ultimate minimum and maximum mooring line tension at fairleads positions by 24% and 8%, respectively, while tower blade loads remained almost unaffected. In [168, 169], researchers investigated the ITI Energy barge [170], moored by catenary lines. Here, the barge consisted of various OWCs to decrease the oscillations, particularly in the structure's pitch and top tower fore-aft modes. A novel active structural control with a complementary airflow control for the OWCs, which controlled the opening of the valves in the chambers, was proposed. The researchers concluded that the platform's pitch angle oscillations and tower top fore-aft displacement decreased drastically by regulating the air pressure inside the OWCs. Ahmad et al. [171] extended the work conducted in [168, 169] by developing a novel control-oriented regressive model to design hybrid systems and implementing a Fuzzy feedback control with numerical tools using air valves to ensure stability for the entire system. The researchers collected representative datasets and trained them in a control-oriented scheme to model the behavior of the hybrid structure. This model was then implemented to reduce the platform's oscillations. The researchers in [172] numerically and experimentally investigated a 32-oscillating water column V-shaped floating structure designed to accommodate WECs and a horizontal axis WT. Specifically, numerical simulations in the frequency domain were carried out and were complemented by wave tank experiments on a 1:50 scale model. A single-point catenary-style mooring arrangement was used for the model, where an anchored chain was connected to a floating buoy and then to the nose of the platform. It was shown that although the platform's pitching motions affected the absorbed wave power by the OWCs, a large pitching angle led to increased accelerations at the hub of a WT. To ensure stability, the pitch resonance period needed to be increased above 1.56 s, as measured during scaled-down tests, corresponding to an equivalent full-scale period of 11 s. In [173], researchers established an aero-hydro-elastic-servo-mooring coupled numerical framework for integrated time-domain dynamic analysis of a hybrid wind-wave floating structure. The results were then compared against data from a 1:50 scale model wave basin test. The proposed hybrid structure consisted of the DeepCwind floating WT [174] and three OWCs, moored with three catenary mooring lines. It was shown that the power take-off control of the OWCs had a beneficial impact on reducing the platform's responses and WT structure loads, resulting in 15% pitch motion mitigation and 6% tower base fatigue load reduction. Recently, in [175], a scaled model test campaign of a floating WT with or without the presence of OWC converters was presented. The structure, which was allowed to oscillate in a heave direction under regular wave trains, consisted of a cylindrical floater with a concentrically integrated OWC. It was concluded that the existence of the OWC reduced the structure's heave motions by a maximum reduction rate of 54.1%. Nevertheless, according to the authors, the study will be further developed to consider the effect of mooring lines and wind turbine control systems in irregular-wave environments.

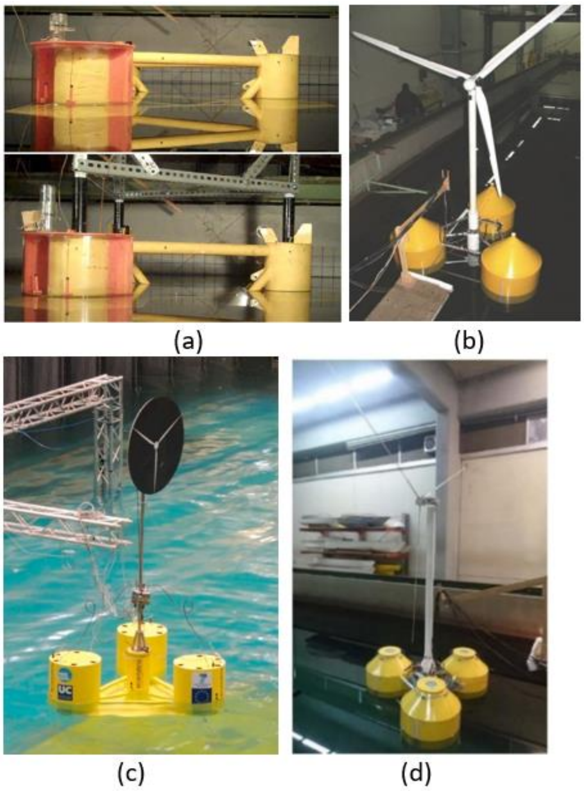


Figure 10 Hybrid OWC systems: (a) WindFLOAT model in the wave tank (adopted from Ref. [162]); (b) tension leg hybrid platform in the wave tank (adopted from Ref [164]); (c) MUP converter in the wave tank (adopted from Ref. [165]); (d) REFOS platform in the wave tank (adopted from Ref. [166]).

Apart from the floating WT concepts, which integrate OWC devices, multi-type WECs enable wave energy to be extracted simultaneously from multiple harvesting methods by one hub. In this context, recent studies have dealt with analyzing hybrid WEC systems. However, most consider a hybrid WEC system with a stationary OWC converter to the wave impact [176-178]. On the contrary, Zheng & Zhang [179] proposed a hybrid WEC composed of a floating cylindrical OWC and several oscillating floats hinged around it. A 3D semi-analytical formulation demonstrated that the hybrid structure could lead to a broader frequency response bandwidth with a higher maximum power capture width than the corresponding ones for isolated OWC and hinged floats.

3.3 OWC Mooring Characteristics

Finally, advances on OWCs with different mooring systems are presented in the following.

3.3.1 OWC & Mooring Systems

Station-keeping systems are required for floating oscillating water column devices to limit the excursion and orientation of the converters under the action of wave-, current-, and wind-environmental forces. Several studies have been presented in the literature focusing on the design of the mooring system of a floating OWC through detailed experimental tests. As aforementioned, [76, 123, 149] focused on scaled-down moored OWC experiments under deep water conditions scenarios, whereas in [61, 133, 180], the experimental research concerned a heave-only OWC model. The results showed that a proper selection of the spring-damper system was beneficial for triggering the dual peak efficiencies and expanding the efficient frequency bandwidth. In their study, Imai et al. [181] investigated the internal wave height and the motions of the converter due to the wave impact through wave tank experiments on a moored BBDB. They concluded that the phase of the internal wave height closely corresponded to the motion of the converter. Krivtsov and Linfoot [182] conducted an experimental campaign on OWC arrays to highlight the effect of the converter-sea interactions on the mooring system from model scale in a laboratory environment to full scale in the open sea.

The study involved testing arrays of three and five similar OWCs with identical mooring systems under similar environmental conditions. The results demonstrated that the mooring loads in the leading mooring line were doubled for both configurations under extreme wave conditions compared to an isolated moored OWC. In [42, 183], the authors presented an experimental and numerical hydrodynamic assessment of a 1:50 scale model of a moored OWC device. The converter was a tension-leg structure with four vertical mooring lines. The study revealed that the device's power efficiency increased near the pumping resonance compared to a fully restrained OWC, attributed to the surge motion of the converter. Regarding the damage survivability of the OWC, it was concluded that a single failure in the mooring system increased the maximum tension by 1.55 times the intact tension.

In contrast, a damaged mooring system could overestimate the maximum tension by more than 20% compared to the tension from irregular wave conditions. The study in [184] presented a model testing campaign of a tension-leg floating OWC under unidirectional regular and irregular wave conditions. It was shown that the model's motions negatively affected the device's hydrodynamic efficiency. Hence, the motion responses should be considered in terms of output efficiency. The study in [185] evaluated the nonlinear motion and mooring line response of a 1:25 scale moored OWC model in regular waves. The investigation considered materials other than chain mooring lines, including nylon rope and iron chain. It emphasized the solid nonlinear effects in the converter's heave motions and the shock loads on the mooring line, particularly for the nylon rope.

Additionally, the study concluded that the damping in the PTO system had a minimal influence on the motions of the OWC, and the tensions in the mooring lines were sensitive to changes in line length. The study in [186] investigated the impact of the mooring system's stiffness on the hydrodynamic performance of floating Oscillating Water Columns (OWCs) through numerical simulations. A 2D wave tank was developed for the simulations, simulating the hydrodynamics of an OWC that was allowed to float only in a sway or heave direction. It was derived that the hydrodynamic efficiency achieved a maximum value at the lowest examined frequency ratio for a surging converter. In contrast, for a heaving OWC, the maximum efficiency was attained for the largest frequency ratio. In addition, the frequency ratio affected the hydraulic efficiency of a heaving converter significantly more significantly, attaining higher vortices than a surging OWC, which presented weaker vortices.

Researchers have also explored the impact of mooring on the efficiency of the Spar buoy OWC in the literature. Connell et al. [187] extended the work from Fonseca et al. [76] by examining the effect of changing some of the Spar buoy mooring characteristics as presented in [76]. They specifically adjusted the masses of the float and clump weight to enhance the power conversion capability of the converter. They developed a numerical nonlinear Froude-Krylov model, incorporating nonlinear kinematics and a 6-degrees-of-freedom integral formulation for the drag forces. The study found that mean drift and peak loads increased with decreased line pretension values while the power efficiency remained unaffected. The performance of the Spar buoy OWC in a wave channel based on a developed time-domain model in linear hydrodynamics, which considered mean drift forces, viscous drag effects, and air compressibility inside the chamber, was presented in [188]. This study extended the work in [77], which tested the Spar buoy using a motion restriction that only allowed the heave motion.

On the other hand, in the experimental and numerical simulations described in [188], the converter was moored to the wave channel by two three-segment lines, with a float and a clump weight attached to each line. The results for regular waves showed a generally good agreement between the numerical and experimental results. They highlighted the poor behavior of the converter at a period in the vicinity of half the roll/pitch natural periods. Irregular wave results agreed well with the converter’s heave motion and pressure difference. On the other hand, discrepancies between numerical and experimental results were observed in surge and pitch outcomes, which were attributed to roll/pitch parametric resonances.

Recently, the hydrodynamic performance of a box-type moored OWC was studied numerically and experimentally. Specifically, in [189], the developed numerical modeling was compared against experimental data obtained from a test campaign in the wave basin with a 1:36 scale model. The study demonstrated that the wave direction significantly impacted sway, roll, and yaw motions while exerting a minimal effect on heave and pitch motions. Furthermore, due to the increased tensions experienced in the mooring lines on the forward side of the converter, a heavier chain on the forward and a lighter chain on the rear lines should be considered in the design process. In the extended analysis presented in [190], three distinct mooring configurations were tested: a tension leg, a taut mooring line, and a catenary mooring line. The surge and pitch motions were inversely proportional to the capture width ratio. In contrast, the taut mooring line configuration performed best, followed by the tension leg and the catenary mooring line.

4. Future Developments

The TRL of offshore OWCs is still relatively low despite the observed momentum in their development. Hence, it has yet to form a full-scale commercial application. The design of floating wave energy converters must ensure their structural integrity in harsh marine environments and improve their invest-ability, making the LCOE competitive in the electric power market. However, although significant progress has been made towards maximizing the wave power efficiency of a floating OWC through the developments above (i.e., multi-device layouts, hybrid structures, OWC and breakwater combinations, and geometry optimization), its growth is often struggled with several geometrical, technical, and structural constraints on its subcomponents. To this end, PTO optimization has played an important role in maximizing power capture on OWCs, whereas control technology systems have been under development in the last decade.

The literature on OWC PTO systems primarily focuses on improving the converter's efficiency through the optimization of air turbine characteristics ([191-193], among others) and the installation of high-speed safety valves [75, 194, 195]. On the other hand, only a few papers deal with the joint study of air turbines and generators, developing control algorithms under different sea states. Falcao [196] applied a stochastic model to devise an optimal algorithm for the rotation speed control of an OWC equipped with a Wells air turbine. The optimal control law expressed a simple relationship between electromagnetic torque and rotational speed. Subsequently, in [197], a detailed analysis of the dynamics and control of air turbines and electrical generators in OWCs was presented. Here, two types of air turbines were considered, i.e., a Wells and a biradial turbine, and their performance was compared with the control strategy and the selected generator. Recently, in [198], a novel control algorithm for a turbine generator set was developed, which maximized power generation without the need to predict the sea state conditions. The algorithm amplified the annual electricity production of a shore-based OWC by 6%.

However, most of the applied methodologies on WEC control technology are model-based, i.e., a mathematical model of the WEC device is required to predict the system dynamics within a specific future time interval as part of the optimal control problem. Well-established model-based algorithms within the state-of-the-art WEC control include, e.g., Model Predictive Control and spectral/pseudo-spectral direct transcription methods [199]. However, the real-time handling of complex models is still limited. Specifically, so far, only the few studies examined joint control techniques on the air-turbine-generator system (i.e., studies [196-198]), whereas other types of controls regarding the generator's rotation speed, rotor resistance, air flow throttle valve operation can be found in [200-202]. This developed control solution can significantly impact the quality of the developed solution, leading to suboptimal performance and losing the overall impact on the target LCOE.

To circumvent this issue and directly tackle the potential loss in performance, advanced data-driven techniques, which would use data from the operational system itself, must be developed, avoiding using first principles (and often a restrictive set of assumptions). The strategies should be able to precisely determine the hydrodynamic characteristics of the OWC, the PTO, and mooring representations for each sea state condition and predict the dynamics of the OWC within the solution of the optimal control problem. These strategies have been presented in [203, 204] and applied to heaving WECs. However, to the author, they have yet to be applied to OWCs.

5. Conclusion

Renewable energy sources as alternative forms of energy supply are attractive since they are inexhaustible and cleaner during operation. Although the wave energy resource amount is lower than other renewable energy sources such as solar and wind, offshore wave energy technology is rapidly developing, motivated by the vast offshore wave potential and fewer restrictions than on shore. The rapid growth of WEC inventions is driven by the necessity to make this technology competitive with fossil fuel power plants. This has prompted numerous studies to focus on optimization strategies for WECs to enhance power efficiency.

This review presents the latest status related to floating oscillating water column devices and introduces the important application trends of OWCs toward the marine environment. Based on the discussions in this review, the following conclusions are drawn:

- Most investigations towards amplifying the OWC power performance have focused on optimization techniques for the converter’s geometry. Different shapes and numbers of oscillating chambers have been considered, efficiently exploiting possible synergies and advances through the fluid’s oscillatory motion.

- Synergies of OWCs with marine structures such as breakwaters allow both the wave energy absorption and the unhindered electricity transmission to the mainland and reduce the wave action intensity on the shore. The amplified wave interaction phenomena due to the wave reflection on the vertical wall can increase by several times the power efficiency under the optimal selection of parameters, such as the wave angle propagation, the distance between the converter and the vertical wall, the length of the breakwater and the formed angle by the wall's arms.
- One promising alternative to increase the performance of renewable technologies is the investigation of the technological feasibility of hybrid systems combining OWCs with WT and/or other types of energy converters. The hybrid system attains lower structural, erection, mooring, foundation, and electric cable costs per MW than stand-alone WECs. Although the rated power of a WEC is much lower than that of a WT, the hybrid structure can cover the operation and maintenance costs on a life-cycle basis, with wave energy production amounting to as high as 5%-7% of the wind energy.
- Methodologies to determine the optimal size, type, and characteristics of the air turbine at the top of the oscillating chamber have also been examined towards the converter's increased performance. These have been coupled with joint control techniques for the air turbine and generators, achieving a significant increase (up to 8%) in average annual electricity generation.

Further research on generic control technology, which could tackle the potential loss in performance, should be developed. In addition, with more installed industry projects and more operation data collected, precise quantitative analysis will assist marine technology in developing efficient wave energy solutions.

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Author Contributions

The author did all the research work of this study.

Competing Interests

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

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