Deliverable 1: OWC Device: State-of-the-art

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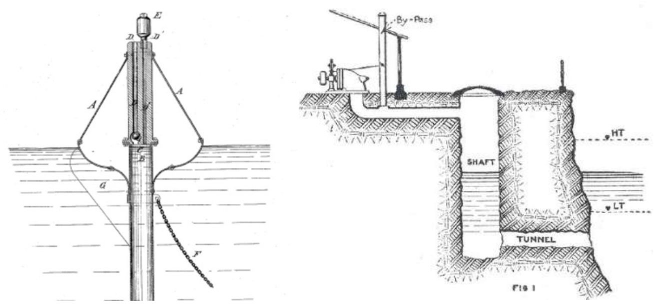
ABSTRACT

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 with respect to other types of energy systems. The Oscillating Water Column (OWC) converters are among the first types of 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 Deliverable provides an overview of the recent floating OWC prototypes and projects, as well as the latest research developments in wave energy converters using the oscillating water column principle. Furthermore, critical structural considerations are discussed, particularly focusing on the converter's geometry and type, and its mooring system design, towards the amplification of the absorbed wave power. It aims to provide a broad overview of the driven parameters and technologies that will be integrated in the overall **ETHOS** approach.

1. Introduction

Wave energy is an abundant renewable source which can provide utility-scale power production through the capture of 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^o and 60^o 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, whereas 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 [5]. Also in 1878 whistling buoys [6] used as a navigation aid, were recorded by the pilots of the New York and Boston streamers (see Figure 1a). In 1895 Isidoro Cabanyes, a Spanish engineer, received a patent for a wave-powered device which used floats to pump water into a reservoir, releasing it to generate electricity [7]. An early device was also constructed by Bochaux-Praceique, around 1910, to provide power to a house near Bordeaux in France (see Figure 1b). This was based on the oscillating water column wave energy technology [8]. Since then, there have been numerous patents filed worldwide. According to [9] the ocean energy technology patents show unequal growth since 1900 with four main faces: (a) years 1900 – 1930 with 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 an 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 the year 1900 up to 2015. Until the year 2025 19,276 patents have been received for ocean and offshore wind technologies [9].



(a) (b)

Figure 1: First known patent 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])

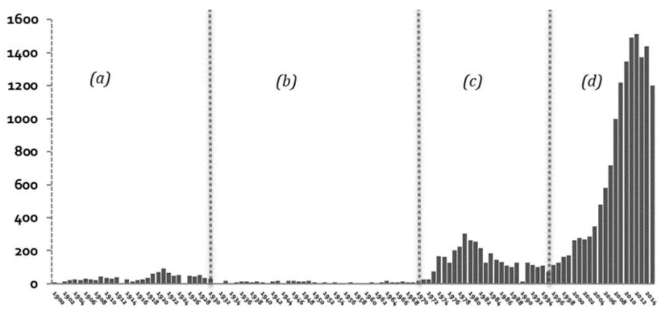


Figure 2. Number of patent families by first priority year for ocean energy technologies over the period 1900 – 2015 (adopted from Ref. [9])

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

Despite the large variation in design, wave energy converters (WECs) can be characterized by location and type [15]. Specifically, WECs can be categorized by their location with respect to the shoreline, i.e., onshore, nearshore, and offshore. As far as their type is concerned WECs can be classified into three predominant types: (a) attenuator, (b) point absorber, (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 the 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].

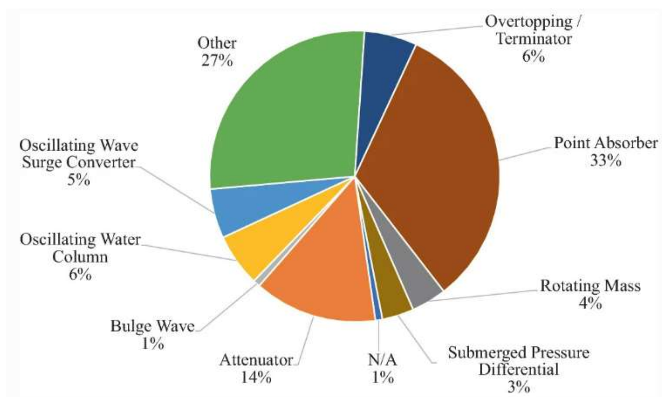


Figure 3: Distribution of wave energy technologies according to EMEC's WEC classification (adopted from Ref. [17])

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 is oscillating above the water free surface. The chamber is connected to the outer atmosphere by a duct housing an air turbine. As the water level rises, the air entrapped within the chamber is compressed, producing a high-speed air flow 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) which are located above the free water surface in a typical OWC system

[18]. Also, OWCs have the ability to operate efficiently even when subjected to low-frequency wave motion, typically around 0.1 [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 through the limitation of the air turbine torque by controlling a by-pass 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 near shore locations to areas of deep water, and from areas of mild wave conditions to locations of extreme waves. However, within the ocean energy sector, there is no clear path towards commercialization. An additional challenge is that the industry is running out of suitable locations and space due to lack of available nearshore sites in heavily contested coastal zones, where there is increasing conflict of other usage. The aim of the present manuscript is to investigate the existing developments on the oscillating water column technology in the open sea, by firstly presenting the evolution of the floating OWC concept, and then by providing an overview of current knowledge. Although there have been numerous studies covering different techniques to capture the ocean waves focusing on OWCs [18], [23] – [26], a dedicated research on floating OWCs in the open sea (where severe climate conditions prevail) have not been presented to the author's knowledge.

The rest of the paper is arranged as follows. In Section 2 the worldwide commercial prototypes concerning the floating oscillating water column technology are presented. Section 3 summarizes the current technology developments for the OWC and their achievements, whereas Section 4 draws conclusions for the application of wave energy in the future.

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, equipped with an air turbine. These buoys were commercialized in Japan since 1965 and are available today from 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 3 years. The device was a barge which measured 80m in length, 12m in breadth and 5.5m in height, and housed several OWCs. Initially it encompassed 22 OWC chambers connected in pairs, out of which three were equipped with air turbines, whereas during the second test campaign, Kaimei had 13 chambers, five of which had been equipped with air turbines, with a nominal 125kW rating. The device was moored with four slack chain lines in the front and one slack rear line and was grid-connected to shore for power transfer. A range of PTO units were tested, including Wells-type and McCormick turbines and more conventional systems with rectification valves [16], [28] – [31].

The power efficiency of the already developed technologies was considerably less than expected and therefore different designs of power systems had to be made. The Backward bent-duct Buoy (BBDB) is a WEC which operates on the same principle as the OWC. It was introduced by Yoshio Masuda in 1986 when trying to improve the energy absorption efficiency of the already 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 worthwhile to mention that the opening duct was initially facing 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 it was first proposed, the BBDB has been studied in various countries and was 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 was subjected to a wide range of wave conditions, including severe storm when the wind speed reached 25-30m/s and the wave height 8.2m [28]. Since that time Ocean Energy has developed several BBDB prototypes with the latest being the OE35, which has been demonstrated under the framework of an EU Horizon Europe Programme entitled as WEDUSEA [33].

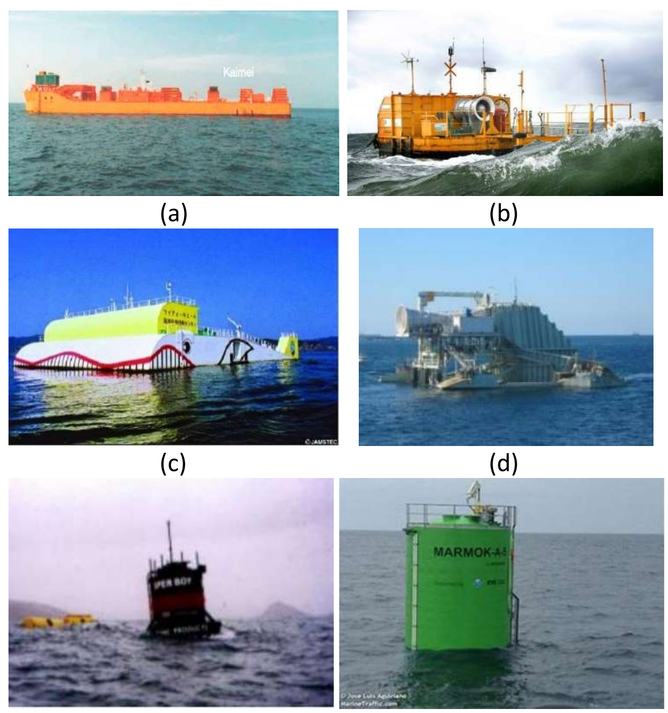
The Mighty Whale was a three-chamber OWC device, developed by the Japan Marine Science and Technology Center in 1998 (see Figure 4c). The device which encompassed a floater with dimensions 50m in length, 30m in width and 12m in height, included two turbines with rated power of 30kW and one turbine with rated power of 10kW or 50kW, 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 [34].

Oceanlinx was a company established in 1997 which specialized in the research and development of ocean based renewable energy technology. The company has deployed Oceanlinx Mk1, a full-scale prototype of 0.5MW installed capacity, at Port Kembla (see Figure 4d). The approximately 500 tons device used a parabolic wall to concentrate the wave energy in its 100 m^2 square meter oscillating water chamber [34]. Its operation started in 2005 and ended in 2009. After the construction of Mk1 device, those of Mk2 and Mk3 followed in the years 2007 and 2010. These were 1:3 scale demonstrators of 1.5MW and 2.5MW rated capacity units, respectively. Unfortunately, the company went bankrupt in April 2014.

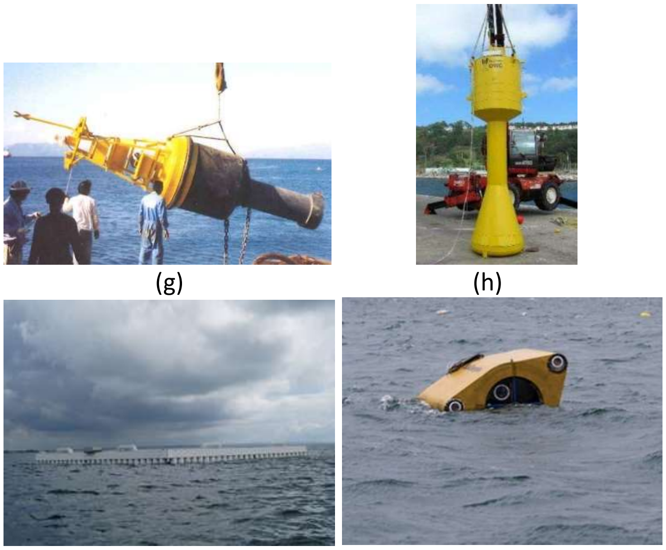
SPERBOY was a floating WEC based on the OWC principle, developed and patented by Embley Energy [36]. In 1999 – 2001 a 1:5 scale demonstrator was deployed at sea (see Figure 4e) which proved the design concept of the product. Nevertheless, since then no progress has been reported in the literature and its current development stage is unknown.

MARMOK-A-5 is an offshore electrical power generator based on the oscillating water column principle with a nominal power of 30kW (see Figure 4f). It is a floating spar type floater of 5m diameter and 42m length (6m are above and 36m are below the water free surface), with a displacement 162Tm. 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 90m, 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, control mechanism [34].

Wave Activated Generator (WAG) is a floating buoy (see Figure 4g) which converts the wave motion into electric power to charge batteries maintained on the buoy with two different voltage ratings, i.e., 12V and 24V. The converter uses the OWC technology with a maximum output of 100W. Five different geometries have been constructed with the overall converter's height ranging between 5.7 – 13.3m, diameter from 1.5 – 3.0m, and total weight from 1.7 – 11.2t [37]. These types of floaters are used in some commercially available buoys to power navigation aids.



(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 [35]); (d) Oceanlinx Mk1 (adopted from Ref[34]); (e) SPERBOY (adopted from Ref [36]); (f) MARMOK-A-5 (adopted from Ref [34]); (g) Wave Activated Generator (adopted from Ref [37]); (h) OWC Spar buoy (adopted from Ref [31]); (i) LEANCON wave energy device (adopted from Ref [43]); (j) SEWEC wave energy device (adopted from Ref [44])

The OWC Spar buoy is an axisymmetric device consisting of a submerged vertical tail tube, fixed to a floater that moves essentially in heave direction. The air flow, displaced by the motion of the OWC inner free surface relative to the buoy, drives an air turbine located 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], [38] – [41] to name a few. Figure 4h shows a picture of the prototype [31] tested at 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 40deg with respect to the incident wave front (see Figure 4i). The floating beams are equipped with two rows of cylindrical OWC chambers. As the wave interacts with the converter the air present in the chambers is pressurized through a high-pressure duct to a turbine [42]. A 1:10 scale prototype was constructed and launched in the sea in July 2015. Each arm had a length of 16.4m and an own weight of 3tn. The converter remained in the sea until December 2015 when it was brought onshore [43]. Today a full-scale prototype of 240m width is constructed with an installed capacity of 4.6MW.

The SEWEC device uses an internal oscillating water column to drive an air turbine and generate renewable energy. Unique to the converter, the OWC and all moving parts are totally sealed-off from the ocean environment (Figure 4j). A 1:50 scale model was tested at the University of Michigan's wave test tank in 2015, whereas in 2016 a 1:20 scale model was constructed and started sea trials [44], [45].

Apart from the floating OWCs (down- or full- scaled) that have been tested in real sea conditions environment, there are also several converters that 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 takes account of wind and tides to ensure that this open end is presented to the incoming waves. The waves repeatedly compress the air trapped within the ducts which is directed to drive an air turbine that generates electricity. An OWEL demonstrator of 350kW was constructed under UK Research and Innovation's funding [46], [47] to operate in early 2013. However, since then there have been no further reports on a full-scale prototype, to the author's knowledge.

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 3m long scaled model was constructed, which included 40 OWC chambers, each damped by an orifice of diameter 14mm [48], [49].

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 is able to take off power from hydraulic bidirectional oscillating movement. Due to its blade pitch variation, the turbine rotates always in the same direction regardless of the direction of the flow. In 2013 a 1:20 scale model was tested in Ifremer wave basin, in Brest France (see Figure 5c), whereas a larger model (i.e., 1:5 scale) is to be built in the near future [50].

The MRC1000 is a floating converter using also the OWC technology. The device consists of six oscillating columns, each tuned to a different range of frequencies for amplified wave energy absorption (Figure 5d). During its development three different PTO systems have been examined. Initially, the oscillating air drove an impulse turbine, whereas at a second stage the turbine drove a hydraulic circuit. At its final design stage, the high-pressure oil drives an electric generator [51]. Various small-scale trials have been performed aiming at the efficient construction of a full-scale prototype of 1MW [52].

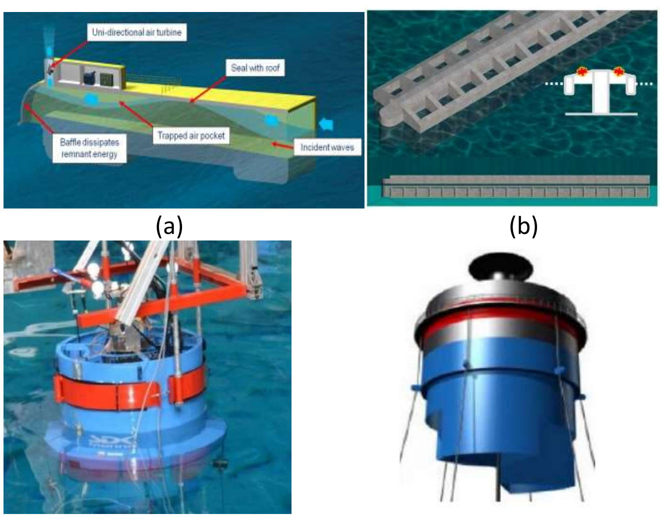


Figure 5. Oscillating Water Column prototypes that are in a design process: (a) OWEL wave energy converter (adopted from Ref. [45]); (b) KNSwing floating WEC (adopted from Ref. [47]); (c) SDK Wave turbine (adopted from Ref. [49]), (d) MRC1000 floating buoy (adopted from Ref. [52])

3. Literature review

There are many publications of past and ongoing studies into floating oscillating water column devices that 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 which drives an air turbine coupled to a generator.

<u>Cylindrical oscillating chamber</u>

The first known hydrodynamic analysis of a floating OWC was applied by McCormik [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. In the numerical method developed in [54], the OWC converter was assumed to consist of two bodies, the first was the floating device and the second was the horizontal rigid thin body with zero mass representing the internal free water surface. In [55] a general formulation of the hydromechanics problem of a floating cylindrical OWC was presented and the corresponding boundary-value problem was solved using the macroelement technique. The method made use of the idealization of the flow around and inside the converter by means of macroelements, of rectangular shape for cross- sections and co-axial rings for vertical bodies of resolution. Falnes [56] provided a thorough consideration of the interaction between waves and OWC devices in the realm of linear potential theory. This work is cited as one of the most complete compilation of mathematical work related to absorption of waves by oscillating bodies. Hong et al. [57] presented numerical estimation of 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 & 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, whereas the second one [59] consisted of two concentric vertical circular cylinders with differentiations in geometry (wall thickness, draught, shape of chamber and turbine characteristics). Three types of first-order boundary value problems were investigated in order to evaluate the velocity potential of the flow field around the device, namely: the diffraction problem, the radiation problem resulted from the forced oscillations of the body in otherwise still water, and the radiation problem resulted 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 one corresponded to the pumping resonance, whereas the second one to the structure's natural frequency. When the pumping and structure resonant frequencies coincide the power capture was low. On the other hand, separation of these frequencies resulted in a significant increase in maximum power capture. These two resonant frequencies, i.e., the natural frequency of the converter and the pumping frequency of the chamber were also examined in [61]. Specifically, a two dimensional fully nonlinear CFD model with dynamic mesh to analyze the performance of a heave-only floating OWC was developed. It was concluded that the efficiency of the converter can be adjusted by the air turbine's damping coefficient and the mooring elasticity coefficient. The resonance frequencies of a floating OWC by employing linear potential flow theory were examined in [62], [63]. It was derived that the pumping natural frequency remained unaffected by the air pressure inside the chamber, whereas the opposite holds true for the natural frequency of the converter. In [64] a CFD model was developed to describe the interactions between regular waves and an OWC, assuming incompressible fluid and viscous flow. The results were compared with an analytical approach which assumed a compressible air flow. From the comparisons it was derived that although slight differences were attained for the water surface elevation inside the chamber, a 30% relative error was experienced in the air flow velocity. Sheng & Lewis [65] investigated the effect of the air compressibility in the chamber of an OWC, on its power conversion and concluded that the dynamic responses of the converter were strongly dependent on the air compressibility. A holistic analytical model of an OWC, including turbine control, for efficient wave energy absorption in the Mediterranean Sea was presented in [66]. From the analysis, which considered two types of air turbines, namely, the Wells type and the axial impulse turbine, the attended annual energy harvesting was calculated. A small-scale OWC device for battery charging was examined in [67]. The authors concluded that a hybrid system of solar and wave energy absorption is the optimum option for annual power supply. In [68] the effect of bathymetry on the efficiency of a floating cylindrical OWC under irregular wave impact was examined. Here CFD methodologies were applied concluding that the irregular wave propagation was not significantly influenced by the channel's bathymetry.

Laboratory experiments on an axisymmetric floating OWC were reported in [69]. Here a two degree of freedom system with an applied damping mechanism was considered. In [70] the hydrodynamic performance of a moored cylindrical OWC was experimentally investigated. 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. It was concluded that the effective frequency bandwidth was increased with the proper selection of the mooring stiffness.

<u>Spar-type OWC</u>

A special case of a floating cylindrical oscillating water column device is the Spar buoy OWC converter which was patented by Falcao et al. [71] in 2020. The geometry of the device was optimized in [72], [73] taking into consideration the air compressibility effect inside the chamber, and a linear characteristic curve of the Wells-type air turbine. This analysis was extended by Henriques et al. [74], [75] who optimized the hydrodynamic shape of the buoy, the characteristics of the turbine and the generator, as well as the control law of the generator 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. The integrity of the device was also verified by experimental measurements on 1:32 scale models in [76]. Here the performance of the OWC Spar buoy and its mooring system was compared for an isolated configuration and a three-device triangular array. It was concluded that the array configuration seems beneficial for wave climates which are 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 [39] the occurrence of parametric resonance, which is a nonlinear phenomenon that induces large roll and pitch motions, in the Spar buoy was examined. Experiments were carried out for a 1:32 scale model and the numerical results were verified. From the analysis it was concluded that the parametric resonance produced a negative impact on power extraction efficiency up to 53%. Recently, Gradowski et al. [78] 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 up to 6.7% and the mass of the converter was reduced up to 11.4%, which could effectively decrease the cost of the converter. Also, in [79] a modified Spar buoy OWC was examined. 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. Experimental results of a 1:10 scale model were presented under regular and irregular wave trains, and non-linear effects caused by viscous flow and turbine damping were introduced.

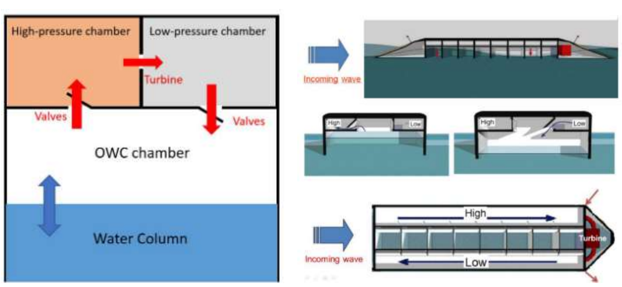
Apart from the Spar buoy OWC converter, another floating spar type device has been thoroughly examined in the literature. The Tupperwave device (see Figure 6a) [80] is a closed-circuit spar-type OWC, which uses non-return valves and two accumulator chambers to create a smooth unidirectional flow across 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 creates a differential of pressure between the chambers which are 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 air temperature increase in the Tupperwave converter.

In addition to the two aforementioned WECs (i.e., Spar buoy and Tupperwave), several other floating spar-type OWCs have been studied in the last years. Indicative study concerns [84] in which a numerical tool was developed, to predict the spar heave motion and the water oscillations inside the structure. The results were validated against experimental outcomes. Also, in [85] the performance efficiency and sustainability of a spar-type OWC was 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 both gas subsystems inside and outside the converter, the net exchange balance, and the interpretation of the OWC as a thermodynamic engine.

Square-type OWC

Besides the OWCs with cylindrical oscillating chambers, numerous floating devices with a rectangular chamber cross section area have been examined worldwide. Lee & Kim [86] determined the wave elevation inside a box-type OWC. Here the results from a theoretical 2D analysis were compared with experimental outcomes. It was derived 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. From their numerical and experimental analysis, it was 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 (named as Seabreath converter -see Figure 6b) formed by a series of aligned rectangular oscillating chambers was examined.

Towards the specification of the device's geometric characteristics scaled wave tank experiments were conducted. From the analysis it was evaluated that for a prototype of 120m long, 24m wide, and 20m high the expected potential production would be 850kW in average. Also, a 40-chamber attenuator-type OWC device (i.e., KNSwing converter) was analyzed numerically and experimentally in [90], [49]. Potential flow-based calculations were conducted and compared well with the experiments. It was found that the ship-like converter demonstrated sea worthiness in even the largest extreme sea conditions, whereas a maximum capture width ration of 30% was measured in regular waves. This value increased up to 37% for short crested waves with large directional spreading. In addition, a weakly compressible smoothed particle hydrodynamics model was developed in [91] and applied on KNSwing converter. Here the air turbine effect was simulated by an equivalent damping force on a thin floating plate inside the chamber, from the heaving displacement of which the motion of the inner water surface was calculated. Recently 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 compared to a two-way wave energy absorption.



(a) (b)

Figure 6. Spar-type and square- type oscillating water column models: (a) Tupperwave converter (adopted from Ref. [80]); (b) Seabreath WEC (adopted from Ref. [93])

Due to the increased interest in recent years on Computational Fluid Dynamics (CFD) modelling, which solve 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. It was concluded that the optimal combination of the submergence ratio and thickness of the chamber's lip achieved a peak efficiency exceeding 0.79. 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 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 energy conversion and mechanical characteristics of an offshore OWC. Here different array configurations of box-type OWCs were examined with and without distance between them. It was concluded that when there was a gap between the chambers, the OWCs had better, or similar comprehensive energy conversion compared to the no gap case.

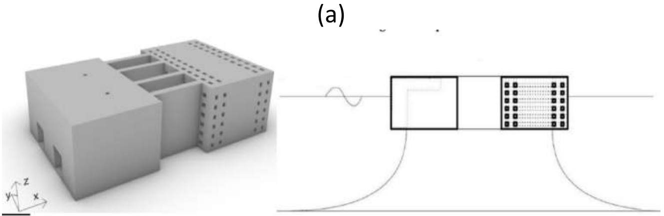
The backward-bent duct buoy (BBDB) wave power device (see Section 2) was examined in numerous studies in the literature. In [98] – [100] the geometrical and hydrodynamic characteristics of the converter were presented, whereas McCormick & Sheehan [101] and later Hong et al. [102] derived that the time-mean drift forces are in reverse direction of propagation of the incident waves, causing the buoy drift into the waves. This was also verified by experimental tests which were presented in [103], [104]. Bull & Johnson [105] developed a linear performance model, in the frequency domain, which linked the oscillating structure to air-pressure fluctuations with a Wells type air turbine for a floating BBDB converter, towards the optimization of its resistive damping. Furthermore, a time domain model for a moored BBDB was developed in [106]. 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 to an annual power production of 530MWhr. Trivedi & Koley [107] explored the yearly-averaged potential of a BBDB in ocean wave conditions. They demonstrated that the average efficiency increased as the incident wavelength became shorter. As far as the geometry of the converter was concerned, a high front wall's draft caused a decrease of the efficiency amplitude, whereas 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. From their analysis it was concluded that the pitching and the heaving motions affected positively and negatively, respectively, the captured wave power.

It is worthwhile to mention 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, as well as on the electricity generation mechanism. This converter (i.e., RM6) was also studied in [110]. Here the WEC's power performance curve in irregular waves was calculated and was proposed that a uniformed water column and a longer horizontal tube length could be beneficial for the produced annual energy. In addition, an alternative proposal for wave energy absorption, based on the BBDB technology, is the forward-facing bent oscillating water column [111]. This converter was theoretically and experimentally studied in [112], [113]. Also, a CFD model was developed in [114] simulating the hydrodynamic interactions between the wave trains and the converter, when the latter was considered moored on the seabed.

Breakwater-type OWC

Breakwaters, both fixed and floating, are typically considered as 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 [115] and [116], respectively. It was derived from the analyses that towards the maximization of the power efficiency the heave motions of the breakwater should be maximum. The opposite held true for the sway motions of the breakwater. In [117], [118] an integrated OWC-breakwater system was examined, concluding to an increase of its performance, in terms of wave transmission and motion responses, under proper selection of the OWC chambers geometry. A floating breakwater integrated with OWC converters was also studied in [119] (see Figure 7a). This study explored how the device configuration, the breakwater width, the pneumatic damping, and the structure's motions influenced the performance of the converters. It was concluded that the integration of multiple devices on the breakwater resulted in improved mean capture width relative to that of a single integrated device. In addition, the device spacing, and the pneumatic damping characteristics should be carefully considered in the design phase, since 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 [119] was extended in [120] covering the impact of the OWCs on the floating breakwater's wave attenuation and motion characteristics. It was found that the pitch motion was the most detrimental motion in terms of OWC efficiency, as well as that OWC integration had a beneficial impact on the wave attenuation and motions of the breakwater. The study [121] 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. From the analysis it was concluded that the performance of the OWCs in irregular waves was equivalent to that observed in regular waves. Furthermore, breakwater motions in irregular waves were found to benefit from the OWC integration with observed reductions in heave and pitch magnitudes. The same held true for regular wave trains. In [122] an experimental analysis on multiple OWCs integrated on a very large floating structure (VLFS) towards the investigation of the structure's pneumatic conversion efficiency was presented. A remarkable mitigation of the structure's heave motion due to the

(a)



(b)

Figure 7. Breakwater with integrated OWC devices: (a) Scaled down breakwater in the test basin of Australian Maritime College (adopted from Ref. [119]); (b) Visual representation of a perforated floating breakwater (adopted from Ref. [128])

presence of the embedded OWCs was found, particularly for longer incident waves. An extension of [122] was presented in [123] in which a laboratory-scale physical model was tested in a wave-current flume in order 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 the pneumatic conversion efficiency up to 46% in specific irregular wave spectra for the floating condition. Zhao et al. [124] examined the hydrodynamic performance of a floating OWC-breakwater system with single-, dual-, and triple-chamber arrangement via a series of 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 the single-chamber OWC. A floating box-type breakwater with dual pneumatic chambers was experimentally studied in [125] in order 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. [126] investigated numerically and experimentally the hydrodynamic characteristics of a novel oscillating water column breakwater which encompassed a horizontal bottom plate. It was concluded that an appropriate length selection of the horizontal bottom-plate can effectively improve the 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. [127] proposed an innovative breakwater solution which encompassed an oscillating buoy converter inside the chamber of an OWC. This configuration was numerically investigated, and the outcomes were compared with an isolated breakwater and an OWC-integrated breakwater system. It was demonstrated that the proposed solution had a beneficial impact on both wave energy conversion and transmitted wave attenuation. Additionally, a double-body floating breakwater which combined an OWC with a perforated floating box was examined in [128] (see Figure 7b). 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. From the carried out numerical simulations it was concluded the wave dissipation effect was superior to that of similar structures, whereas the width of the OWC opening and the water depth had a great influence on 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 a better wave dissipation.

Breakwater & OWC converters

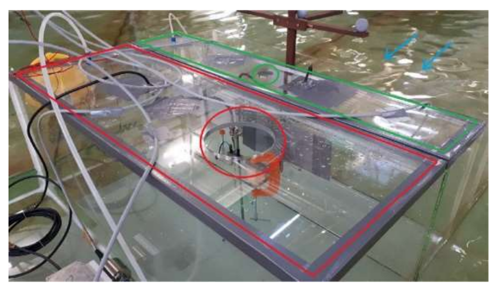
In addition to breakwater integrated wave energy converters, OWCs located at a distance from breakwaters have been also considered in the literature. Specifically, breakwaters and oscillating water column converters have been primarily combined with large floating structures towards the reduction of the latter structural deflections. Hong et al.

[129] 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 Kelvine-type Green function in a finite depth water. It was concluded that the presence of the OWC in front of the VLFS reduced significantly the latter vertical displacements. Subsequently, in [130] the aforementioned forward-facing bent OWC was connected by a pin with the VLFS. Here, the Bernoulli-Euler beam equation for the structure was coupled with the OWC's motion equations. It was shown that the deflections, bending moments, and shear forces of the VLFS in waves were reduced due to the presence of the pin-connected OWC. The feasibility of integrating a VLFS with multiple wave energy converters combining OWCs and oscillating flaps (OF) was examined in [131]. In this study a time-domain numerical problem based on the modal expansion theory and the nonlinear potential flow theory was applied to optimize the size and layout of an array of OWCs and OF placed in front of a VLFS. A higher energy conversion was achieved compared to a single OWC and OF due to the beneficial wave interaction phenomena, which in turn reduced the hydroelastic response of the VLFS. This was further amplified as the distance between the OWC and the structure increased. As far as the chamber's width was concerned the energy conversion efficiency decreased with chamber width in short-period waves and vice versa in long period waves.

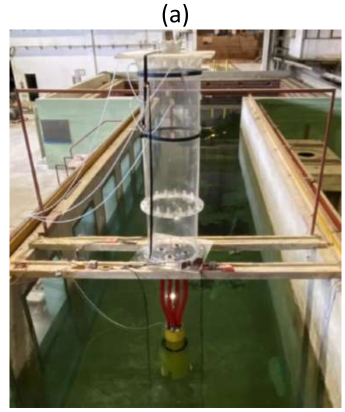
Recently, the amplified incoming wave energy in front of a breakwater, due to the scattered and reflected waves originating from the presence of the vertical wall, has triggered increased interest in wave energy conversion systems operating near a breakwater. Konispoliatis & Mavrakos [132] dealt with the investigation of 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 the one of an array of two OWCs consisting of the initial and its image virtual converter with respect to the vertical wall, that were exposed to the action of surface waves without the presence of the breakwater. It was concluded that the amplified wave interaction phenomena between the members of the array (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 an appropriate selection of the distance between the device and the breakwater. In [133] a novel WEC-breakwater system composed by a heaving OWC device and a stationary breakwater was proposed. Here the corresponding scattered and radiation problems were solved in the realm of potential flow theory. It was found that when the distance between the converter and the vertical wall was well-tuned against the wavelength, in order to satisfy the sloshing mode inside the water gap, the power extraction by the converter was maximized. Ram et al. [134] 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 that the optimal performance was attained for the highest examined wave frequency (i.e., 4.833 rad/s), whereas 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 [135], [136] and an OWC converter placed in front of a V-shaped vertical wall [137]. In both studies a remarkable wave elevation and power capture efficiency was observed, which increased as the breakwater's formed angle decreased.

Multiple chamber-type OWC

With the aim of broadening the wave-frequency bandwidth of increased power efficiency by a floating oscillating water column device the concept of multiple chamber converters has been proposed. Initially, OWCs with multiple chambers were considered for possible integration on floating breakwaters ([118], [125]). In addition, Shalby et al. [138] developed a numerical model in 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 framework of linear potential wave theory. In [139] the hydrodynamic performance of a 2D dual OWC system with a gap, composed of two offshore heaving OWCs and an onshore unit was numerically investigated using CFD methodologies. This combination of converters aimed to increase the wave power performance while dissipating the reflected wave energy. From the analysis it was concluded that a small draft of the front OWC's back lip, as well as a high spring stiffness were more advisable for the high performance of the whole system. Subsequently, Xu et al. [140] 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 in small wave height the catenary anchor system was the preferable mooring option in terms of energy absorption. On the other hand, the power performance of the converter was improved in large wave heights when moored by a compact mooring system. Moreover, it was demonstrated that mooring tensions attained great nonlinearities which were amplified for the synthetic fiber ropes, whereas the opposite held true for the fatigue damage of a chain mooring since it was greater than that of synthetic lines. The study [140] was extended in [141] 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 8a). It was shown that in surge motion the natural frequency of the system was much lower than the generated waves, while in some cases the device followed the incident wave motion due to negative 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, which was faced up directly to the incident wave train, and a real chamber with indirect interactions with the propagating waves, was theoretically, numerically, and experimentally studied in [142], [143]. It was revealed that the device was capable of converting all the energy of the incoming waves to pneumatic power in specific wave conditions which was rarely detected in other types of WECs. Specifically, 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. [144], [145] focused on the coaxial-duct OWC converter, a new floating OWC concept which consists of two coaxial cylindrical ducts interconnected at their bottom ends (see Figure 8b). The outer duct is open to the sea at its top, whereas the inner duct extends above the sea level and is connected to a self-rectifying air turbine. From the conducted experiments of a 1:40 scale model, in regular and irregular waves and various damping conditions, it was concluded that compressibility effects had constructive and destructive effect on the mean absorbed power at specific wave frequencies. The relative magnitude of positive to negative (or negative to positive) compressibility effects between transition regions was separated by critical points which were categorized as *Equicompressum Nullum* and *Equicompessum*. Knowledge of these critical points could bring important implications for the control of the OWCs.



(a)



(b)

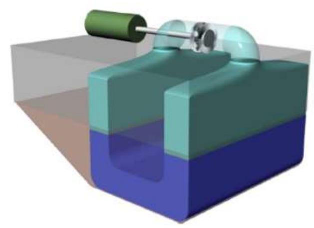
Figure 8. Dual chamber OWC devices: (a) Scaled down model of two chambers (the rear chamber is in red color, and the front in green. Blue arrows indicate the wave train direction)

(adopted from Ref. [141]); (b) Scaled down coaxial-duct OWC converter (adopted from Ref. [144])

OWC of a random geometry

It terms of the principle for the wave energy extraction under the oscillating water column technology several prototype models have been developed in recent years, with different operation principles from the aforementioned ones. UGEN, a floating device with a U tank for generation of electricity from waves was firstly introduced and patented by Instituto Superior Tecnico in 2010 [146]. The device is composed of an asymmetric floater and a PTO system of a self-rectifying air turbine directly coupled to an electrical generator (see Figure 9a). The motion of the U-shaped OWC, which is mainly induced by the rolling of the floater, forces the air through the air turbine to absorb the wave energy. A numerical model and assessment of the converter was presented in [147], [148], which demonstrated the existence of two natural periods, i.e., the rolling and the U chamber's natural periods. It was concluded that the system performed better if the two natural periods were separated, and especially for a period range in the vicinity of the rolling natural period. In addition, in [149] 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 geometry. The converter was experimentally validated in [150] with a 1:24 scale model under regular and irregular wave conditions. 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 which affected power extraction and increased the mooring line loads.

Inspired by the multiple-chamber OWCs a novel 3D multi-chamber OWC wave energy converter (MCOW) has been proposed in [151]. It consists of two hulls, of 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 0-120deg (see Figure 9b). The device is moored to a catenary-buoy using a single point mooring system which allows the opening angle of the hulls to face the incident wave. The study [151] dealt with the experimental verification of the proposed concept using a 1:30 scale model. The effects of the wave amplitude and the converter's geometrical characteristics were



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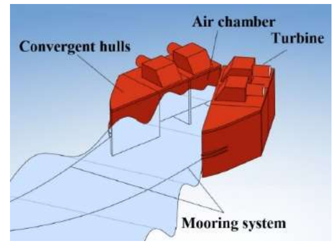

(b)

Figure 9. OWC of a random geometry: (a) 3D representation of the UGEN converter (adopted from Ref. [149]); (b) 3D representation of the MCOW converter (adopted from Ref. [151])

investigated in relation to the converter's hydrodynamic performance. It was concluded that the hydrodynamic efficiency of the converter increased as the draught and the wave amplitude decreased, whereas from the efficiency comparison of the two chambers it was derived that the rear chamber had a lower efficiency compared to the front one which should be carefully considered during the design of the system. Other recent studies in the field of OWC's geometry-optimization are [152], [153] which studied a toroidal converter and a rectangular OWC with an elliptical front wall. Specifically, in [152] the Galerkin's method was applied for the solution of the corresponding diffraction and radiation problems in the frequency domain. From the analysis it was concluded that a toroidal OWC with a cylindrical oscillating chamber attained an increased wave power efficiency compared to the one of a toroidal converter with a toroidal chamber. In [153] a 2D numerical simulation method was applied for the evaluation of the inner air pressure variation and outlet air flow of an OWC with various elliptical wall geometric characteristics. The elliptical front wall improved the energy conversion effect up to 25% compared to the efficiency of an OWC with a rectangular wall.

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 1980s, Falnes & McIver [154] applied a mathematical description, based on linear theory, for a system of OWCs. It was shown that with optimum oscillation amplitudes all the incident wave power can be captured. In [155], [156] an array of interacting free-floating OWCs devices, which were either floating independently or as a unit, was examined. An analytical solution method of 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 the presence of a coaxial solid vertical cylinder. It was concluded that the array spacing can significantly effect the total power output especially when the inter-body distance in the array is close to the wavelength. The effect of the inter-body spacing on the eigenfrequencies of an OWC array in an equilateral triangle was examined in [157]. It was shown that the maximum power may be absorbed at a given distance for which the damping of the dominant eigenmode is less than that of a single converter. An array of floating OWCs of an arbitrary shape was studied in [158] which presented the development of a numerical methodology for the linear and nonlinear wave force, motion response, and wave power absorption evaluation. Here, the geometry of the OWC was optimized by attaching an arc-shaped reflector to the rear bottom of the converter or by locating the device on a submerged caisson. A series of significant peaks characterized the wave energy harvesting were observed, which were not only associated with the entrapped fluid resonant motion, but also to the resonant frequencies of the rigid-body motions.

Two of the aforementioned commercialized OWC prototypes, i.e., the MARMOK-A-5 and the OWC Spar buoy, when they considered as part of an array of converters were examined in [159], [160]. Specifically, in [159] a state-space model for the simulation of an array of OWCs with nonlinear power take off dynamics was developed. The simulation results showed that the employment of an OWC in an array and consequently the wave interactions, can widen the desirable range of regular wave frequencies for energy conversion, whereas in irregular waves the cross-body interactions were found to be negligible at specific distances between the members of the array. In [160] a numerical analysis of a triangular array of Spar buoy OWCs, with bottom and inter-body mooring connections, under regular and irregular wave train interactions was presented. For regular waves a coupling effect between surge/sway and heave motions was observed, whereas the converters' average heave amplitude decreased 6.8%. Furthermore, the simulations with a set of uni-directional irregular wave trains showed that an angle of 30deg of the incoming wave provided better results for the examined mooring configurations.

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], [115], [140] focused on scaled down moored OWC experiments under deep water conditions scenarios, whereas in [61], [125], [161] 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, as well as for expanding the efficient frequency bandwidth. Imai et al., [162] presented wave tank experiments on a moored BBDB. They investigated the internal wave height and the motions of the converter due to the wave impact and concluded that the phase of the internal wave height was close to motion. Krivtsov & Linfoot [163] conducted an experimental campaign on OWC arrays to highlight the effect of the converter-sea interactions on the mooring system from model-scale in laboratory environment, to full scale in the open sea. Arrays of three and five similar OWCs, with identical mooring systems, were tested under similar environmental conditions. It was shown that the mooring loads in the leading mooring line, under extreme wave conditions, were doubled for both configurations in comparison to an isolated moored OWC. An experimental and numerical hydrodynamic assessment of a 1:50 scale model of a moored OWC device was presented in [40],

[164]. The converter was a tension-leg structure with four vertical mooring lines. It was found that the device's power efficiency increased at the vicinity of the pumping resonance compared to a fully restrained OWC due to the converter's surge motion. As far as the damage survivability of the OWC was concerned, it was concluded that a single failure in the mooring system increased the maximum tension by 1.55 times the intact tension, whereas a damaged mooring system could result in overestimating the maximum tension by more than 20% in comparison to the tension from irregular wave conditions. A model testing campaign of a tension-leg floating OWC under to both unidirectional regular and irregular wave conditions was also presented in [165]. It was shown that the hydrodynamic efficiency of the device was negatively affected by the motions of the model. Hence the motion responses should be taken into consideration in terms of the outputted efficiency. In [166] the nonlinear motion, and the mooring line response of a 1:25 scale moored OWC model in regular waves was evaluated. Here apart from chain mooring lines, also other materials such as nylon rope and iron chain were investigated, highlighting the strong nonlinear effects in the converter's heave motions and the mooring-line shock loads for the nylon rope. Furthermore, it was concluded that the PTO damping had a very limited influence on the OWC's motions and that the mooring tensions were sensitive to the variation of the mooring line length. The effect of the stiffness of the mooring system on floating OWCs on the latter hydrodynamic performance through numerical simulations was investigated in [167]. Here a 2D wave tank was numerically developed to simulate the hydrodynamics of an OWC which was allowed to float only in 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, whereas 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 stronger, attaining also higher vortices, than that of a surging OWC, which presented weaker vortices.

The mooring-effect on the efficiency of the Spar buoy OWC has also been examined in the literature. Connell et al. [168] extended the work from Fonseca et al. [76], by examining the effect of changing some of the Spar buoy mooring characteristics as were presented in [76]. Specifically, the float and clump-weight masses were modified towards the increased power conversion capability of the converter. A numerical nonlinear Froude-Krylov model, which included nonlinear kinematics and 6dofs integral formulation of the drag forces was developed. It was found that the mean drift and peak loads increased as the line pretension values decreased, whereas the latter values did not affect the power efficiency. The performance of the Spar buoy OWC in a wave channel based on a developed time-domain model in the realm of linear hydrodynamics, which considered mean drift forces, viscous drag effects and air compressibility inside the chamber, was presented in [169]. 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 which were described in [169] the converter was moored to the wave channel by two three-segment lines, with a float and a clump weight attached on each line. The results for regular waves showed a generally good agreement between the numerical and experimental results and highlighted the poor behavior of the converter at a period in the vicinity of half the roll/pitch natural periods. Irregular wave results presented a good agreement for the converter's heave motion and pressure difference, whereas in surge and pitch results some discrepancies between numerical and experimental results were attained, which were attributed to the existence of roll/pitch parametric resonance.

Recently, the hydrodynamic performance of a box-type moored OWC was studied numerically and experimentally. Specifically, in [170] the developed numerical modelling was compared against experimental data from a test campaign in the wave basin with a 1:36 scale model. It was shown that the wave direction had a prominent effect on sway, roll and yaw motions, and a minimal effect on heave and pitch motions. Furthermore, due to the increased tensions experienced in the mooring lines in 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 designing process. The analysis was extended in

[171] where three different mooring configurations were tested, namely, a tension leg, a taut mooring line, and a catenary mooring line. The surge and pitch motions were found to be inversely proportional to the capture width ratio, whereas the taut mooring line configuration was the best performing, followed by the tension leg and the catenary mooring line.

Hybrid OWC systems

One promising alternative to reduce the cost and increase the performance of renewable energy technologies is the application of hybrid systems which combine offshore wind turbines (WT) with OWCs converters, and/or wave energy converters of different operation principles into one hub. Although these hybrid systems are still far from commercial use, several studies based on the integration of oscillating water column devices onto floating WTs have been reported in the marine sector in an early stage of application. Aubault et al. [172] proposed a floating structure for multi-megawatt WT combined with an OWC. The structure was a three-column semi-submersible platform which encompassed an OWC converter at one of the floater-columns (see Figure 10a). They developed a numerical model, which was validated experimentally, to account for the effect of coupling between the OWC PTO and platform's motions. It was shown that the effect of the oscillating air pressure in the chamber on the platform's responses was limited, leading however to a small increase in pitch and roll motions. In [173] a tension leg platform of three hydrodynamically interacting OWCs and a 5MW WT was presented. Here a coupled-hydro-aero-elastic formulation was developed in the frequency and time domain taking into consideration the floater's hydrodynamics and the WT's aerodynamics loads. It was concluded from the analysis that the air pressure head inside the chambers had little influence on the structure's surge motions. On the contrary, tension forces along the mooring tendons were very dependent on the air pressure variation. The work was extended in [174] which concerned 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 by means of small thrusters mounted at the level of the WT nacelle. It was shown that the inner pressure, therefore and the mooring line tension forces decreased while the orifice diameter increased, whereas the orifice diameter did not affect the surge motions of the structure. Sarmiento et al. [175] presented experimental ocean basin tests of a multi-use platform (MUP), which was moored with conventional mooring lines and encompassed three OWCs and a 5MW WT (see Figure 10c). Here, the wind effect was simulated with a portable wind generator and the wind turbine as a drag disk, whereas the OWCs air turbines were conceptualized by different diameter openings on each OWC chamber. It was evidenced that different wind velocities did not affect the chambers dynamics. In addition, the existence of the WT introduced higher motions and mooring systems loads, whereas the OWC effect was limited. Konispoliatis et al., [176], [177] studied a multi-purpose floating TLP structure, named as REFOS, which consisted of three OWCs converters and a 10MW 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. The results from the analysis were complemented by wave tank experiments on a 1:60 scale model. Here the air turbines' PTO was simulated by perforated carpets at the top of the chambers, whereas only the steady aerodynamic thrust was accounted for by applying a pulling force through a horizontal string attached to the nacelle height at the one end, while at the other end a weight equal to the nominal wind turbine thrust load was suspended, using a suitable pulley. It was concluded that the wind velocity did not seem to affect the responses of the hybrid structure. On the contrary, the air turbine characteristics dominate the structure's motions and tension forces. It was found that the presence of the

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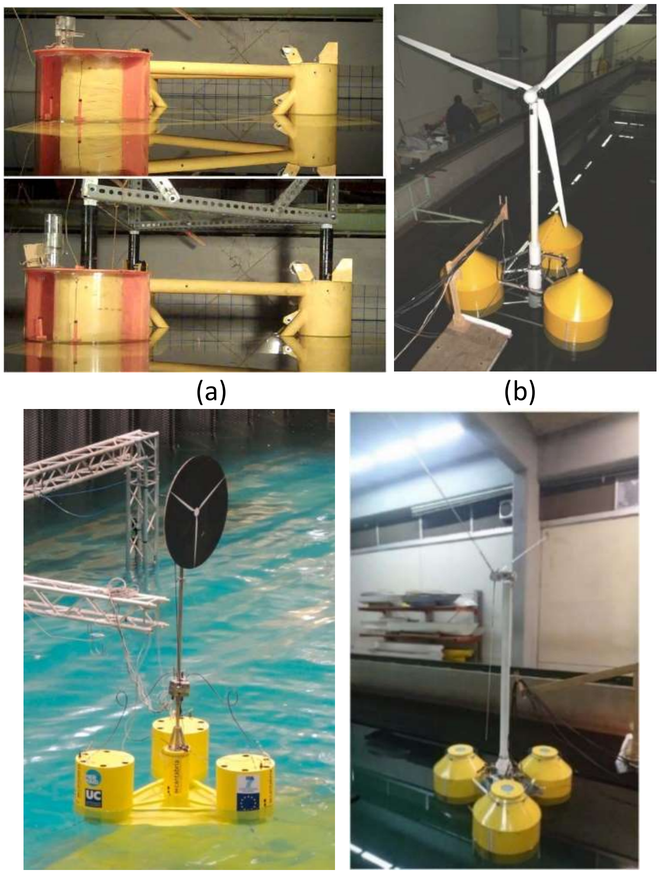
Με τη χρηματοδότηση της Ευρωπαϊκής Ένωσης NextGenerationEU



(a) (b) (c) (d)

Figure 10. Hybrid OWC systems: (a) WindFLOAT model in the wave tank (adopted from Ref. [172]); (b) tension leg hybrid platform in the wave tank (adopted from Ref [174]); (c) MUP converter in the wave tank (adopted from Ref. [175]); (d) REFOS platform in the wave tank (adopted from Ref. [176])

OWCs increased in absolute value the ultimate minimum and maximum mooring line tension at fairleads position by 24% and 8%, respectively, whereas tower blade loads remain almost unaffected. In [178], [179] the ITI Energy barge [180] moored by catenary lines was investigated. Here the barge consisted of various numbers of OWCs to decrease the oscillations, particularly in pitch and top tower fore-aft modes in the structure. A novel active structural control with a complementary air flow control for the OWCs, which controlled the opening of the valves in the chambers, was proposed. It was concluded that through the regulation of the air pressure inside the OWCs the platform's pitch angle oscillations and tower top fore-aft displacement were decreased drastically. Ahmad et a. [181] extended the work conducted in [178], [179] by developing a novel control-oriented regressive model for the design of hybrid systems and implementing a Fuzzy feedback control with numerical tools using air valves to ensure stability for the entire system. To do so, representative datasets were collected and trained a control-oriented scheme to model the behavior of the hybrid structure, which in turn was implemented to reduce the platform's oscillations. In [182] a 32-oscillating water column V-shaped floating structure to accommodate both WECs and a horizontal axis WT was numerically and experimentally investigated. Specifically, numerical simulations in the frequency domain were carried out and were complemented by wave tank experiments on a 1:50 scale model. The model was moored with a single point catenary style arrangement, 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, large pitching angle leaded to increased accelerations at the hub of a WT. Hence for stability purposes the pitch resonance period needed to be increased above 1.56s which were measured during scaled-down tests and corresponded to an equivalent full-scale period of 11s. In [183] a aero-hydro-elastic-servo-mooring coupled numerical framework for integrated time-domain dynamic analysis of a hybrid wind-wave floating structure was established, whereas the results were compared against a 1:50 scale model wave basin test data. The proposed hybrid structure consisted of the DeepCwind floating WT [184] 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 the reduction of the platform's responses and WT structure loads, resulting in 15% pitch motion mitigation and 6% tower base fatigue load reduction. Recently, in [185] 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 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 in order to take into consideration the effect of mooring lines and wind turbine control system in irregular-wave environment.

Apart from the floating WT concepts which integrate OWC devices, multi-type WECs enable wave energy to be extracted from multiple harvesting manner simultaneously by one hub. In this context recent studies have dealt with the analysis of hybrid WEC systems. However, the majority of them consider a hybrid WEC system with a stationary OWC converter to the wave impact [186] – [188]. On the contrary, Zheng & Zhang [189] proposed a hybrid WEC, which was 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 wider bandwidth of frequency response with a higher maximum power capture width compared to the corresponding ones for an isolated OWC and hinged floats.

4. 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 compared to other renewable energy sources such as solar and wind, the offshore wave energy technology is rapidly developing, motivated by the vast offshore wave potential and fewer restrictions than on shore. The fast-growing rate on WEC inventions is being spurred by the need to bring this technology to a competitive level with fossil fuels power plants. This has triggered many studies to deal with the optimization strategies for WECs towards amplified 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 the amplification of the OWC power performance have been focused on optimization techniques for the converter's geometry. Different shapes and number of oscillating chambers have been considered exploiting possible synergies and advances through the fluid's oscillatory motion in an efficient manner.
- Synergies of OWCs with marine structures such as breakwaters allow both the wave energy absorption and the unhindered electricity transmission to the mainland, as well as 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. In this respect the hybrid system attains lower structural, erection, mooring, foundation, and electric cable costs per MW compared to stand-alone WECs. It has been noted that although the rated power of a WEC is much lower than that of a WT, the wave energy production amounts as high as 5% - 7% of the wind energy, covering the operation and maintenance costs of the hybrid structure on a life-cycle basis.
- Methodologies to determine the optimal size, type, and characteristics of the air turbine at the top of the oscillating chamber have been also 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 the optimization of the converter's geometric characteristics as well as on a a 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 to develop efficient wave energy solutions.

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