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An Overview of the Oscillating Water Column (OWC) Technologies: Issues and Challenges

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Abstract:

There is a vast amount of energy available in ocean waves which can contribute to provide the electricity supply specially for countries surrounded by the ocean. This paper provides background knowledge in different techniques to harness the kinetic and potential energy in wave power along with an overview of the recent developments in Oscillating Water Columns Wave Energy Converters. The main purpose of this study is to provide a thorough review on the current state of the technology and methods in Wave Energy Converters and to help scientists to find the future potential and gaps in this area. Moreover, significant research opportunities are identified based on the literature review of the existing research studies, and research problems to be addressed are presented and can be used as tool for the future research in this area.

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1. INTRODUCTION

Ocean waves are a clean energy resource with the potential to make a significant contribution to the global energy demands as progress is made toward a more sustainable world. A key attraction is the predictability of energy supply, which is advantageous in terms of stabilizing electrical grids compared to less predictable solar and wind energy resources. Table **1** depicts the theoretical potential of wave energy for different regions. However, the potentially useable wave energy capacity on a global basis is estimated to be between 2,000 and 4,000 TWh/year [1], which is far less than the global theoretical potential of wave energy (29,500 TWh/year) shown in Table **1**. This reveals that marine energy development is still in its infancy, specifically in the context of wave power. Therefore, it is vital to develop a framework to efficiently capture and harvest the energy delivered by the waves. Another important issue is the need for proper construction to survive in the sea environment, especially in storm situations where the wave power increases dramatically. Floating equipment capable of being installed offshore has been introduced in recent decades. The systems can be designed and optimized to take advantage of both potential and kinetic energy, either separately or simultaneously [2]. The future of this industry is difficult to forecast since there are no large-scale wave farms; however, as technology advances, new chances to develop wave energy harvesting become available [3].

Table 1: Wave Energy Potential Around the World [4]

Regions	Wave energy potential (TWh/year)
New Zealand, the Pacific Islands, and Australia	5600
Asia	6200
South America	4600
North America and Greenland	4000
Africa	3500
Western and Northern Europe	2800
Central America	1500
The Mediterranean Sea and Atlantic Archipelagos	1300
Total	29,500

Figure **1** depicts the total wave power distribution for distinct coastal habitats, as reported by the National Oceanic and Atmospheric Administration's Wave Watch III data [5]. As shown by these statistics, sites in North America have more wave energy potential than sites in Europe, even though this region conducts the majority of wave energy converter (WEC) studies. From Figure **1** it is apparent that the power that can be extracted from wave energy is greatest around Australia, followed by the United States and Chile, with Portugal and France having substantially smaller values.

The literature review of the existing development of novel solutions that enhance the performance of existing Wave Energy Converter (WEC) technologies is the aim of this study. The WEC has a lot of opportunities for boosting energy conversion and benefiting society while lowering the carbon footprint and preventing additional damage to the ecosystem. Unlike solar energy, which is dependent on clear weather, and wind energy, which is hard to anticipate and requires a large area of space, wave energy is a constant source that can be incorporated into other systems.

Offshore Renewable Energy has a great potential to play a major role in supplying the energy demand and facing climate change impacts. There are different types of offshore energy converters including wind and wave energy and each category has different models based on the type of generation, foundation, and type of transmission. In this paper, a complete overview of offshore wave and wind energy including different types, current possibilities for improvement and the main challenges are discussed. The main purpose of the research is to cover different techniques to capture the ocean waves along with focusing on Oscillating Water Column (OWC) Wave Energy Converter (WEC) energy chain mechanism and practical and theoretical methods to convert tidal movement into electricity. The paper has been structured as follows:

In Section 2 various type of WECs are presented. In Section 3 existing OWC technologies are discussed. In Section 4, first, different method of studies in the integrating OWC and Breakwater are reviewed, followed by arrays of OWCs studies to demonstrate performance differences. Second, previous studies that used computational fluid dynamic (CFD) approaches to simulate the performance of OWC systems are discussed. Third, hybrid wave-wind studies are reviewed. Finally, the studies that examined the large-scale OWC systems are analysed. In Section 5 research opportunities and discussions are presented, and a conclusion is given in Section 6.

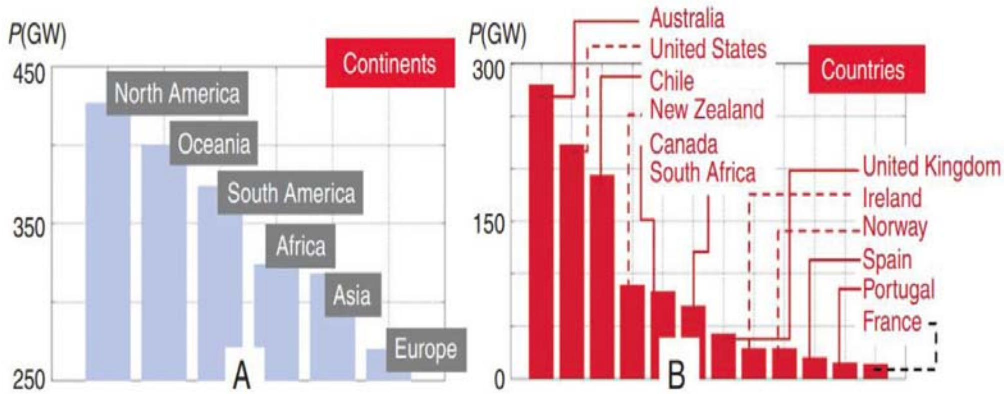


Figure 1: Estimated yearly means wave power for (**a**) continents and (**b**) countries [5].

2. OFFSHORE WAVE ENERGY CONVERTERS

WECs transform the kinetic and potential energy generated by a passing wave into practical mechanical or electrical energy that can be used for a variety of applications range of applications. These range from the supply of clean energy to the electrical grid to pumping for saltwater desalination. The methods employed for wave energy conversion are numerous, as evident from the knowledge that 1000 patents in the area exist worldwide [6]. The first WEC was invented in France, and the first WEC patent was acquired in 1799. Yoshio Masuda invented the predecessor of contemporary wave energy systems in Japan in 1940 [6].

Figure **2** depicts various types of WECs based on their operating characteristics and operating location, which can be onshore, nearshore, or offshore. As shown, WECs are classified into eight main categories, namely: “attenuator, point absorber, oscillating wave surge converter, oscillating water column, overtopping/terminator device, submerged pressure differential, bulge wave, and rotating mass”. The only model which is most prevalent in onshore systems is the oscillating water column in which the air is trapped in a semi-submerged cylinder and compressed to cause rotation of a turbine and produce power as a result [7]. In the following paragraph, the mechanisms of each WECs technology in harvesting energy will be discussed in more detail.

2.1. Attenuator

Figure **2a** shows the schematic of an attenuator device. The attenuator is a piece of floating equipment that runs parallel to the axis of the wave and harvests energy when passing waves resulting in a difference in velocity between the two arms. The initial commercial form of this mechanism looks like a snake called Pelamis Wave Power and can have a total length of 150m with a rated power of 750kW and can be installed in water depths more than 50m [9].

The current commercial Pelamis wave energy converter farm which has 22.5MW output power can be considered the first commercial offshore wave energy converter and has 120m long and 3.5m wide and wights 750t the first phase of the project was installed in 2008 in Portugal [10].

2.2. Point Absorber

As shown in Figure **2b** the point absorber is equipment with a smaller size compared to the wavelength. The pressure difference allows the floating structure to be lifted and down on the water's surface or immersed beneath the water's surface. This type of converter can absorb wave energy in all directions, and they install offshore at the surface of the water. The first commercial project consisted of 12-21 floater heaving floaters and to generate the power it was connected to a hydraulic system which converts vertical motion into a rotational movement that drives the hydraulic system [11].

2.3. Oscillating Wave Surge Converter

Oscillating wave surge converters are presented in Figure **2c**. The oscillating wave surge converter typically has a hinged deflector perpendicular to the axis of the wave and slides back and forth, taking advantage of the wave's horizontal particle motion. In reaction to the movement of the waves, the arm fluctuates as a pendulum on a pivoting connection. One of the commercial scale projects is Oyster 800 which is a nearshore wave energy device and can be deployed to up to 15m of water depth with an output power of 800kW [12].

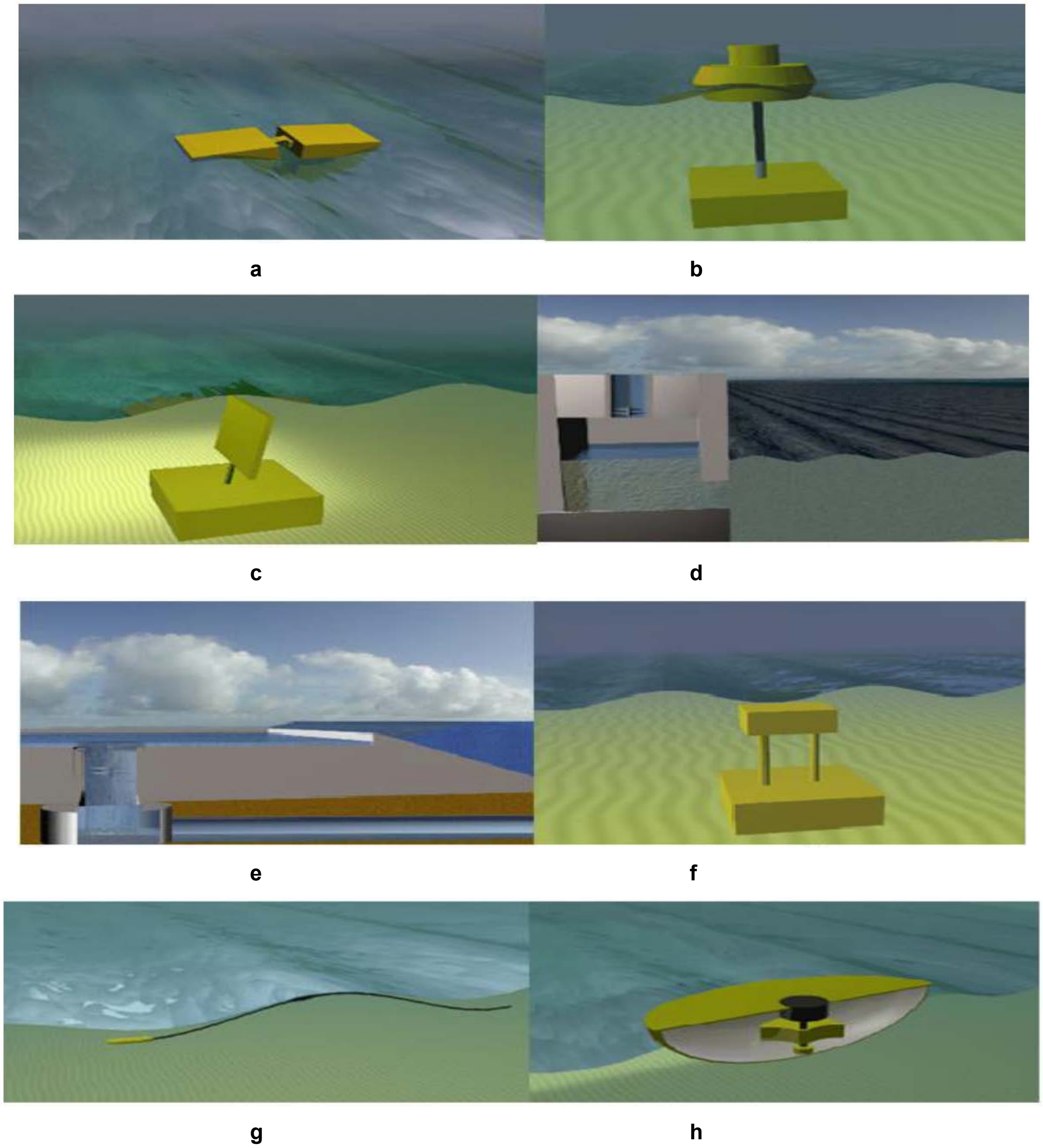


Figure 2: Main classifications of WECs: (**a**) attenuator, (**b**) point absorber, (**c**) oscillating wave surge converter, (**d**) oscillating water column (OWC), (**e**) overtopping device, (**f**) submerged pressure differential, (**g**) bulge wave, (**h**) rotating mass [8].

2.4. Oscillating Water Column (OWC)

Figure **2d** depicts the schematic of an OWC. The oscillating water column (OWC) is a partly immersed cylindrical construction, which is accessible to the ocean under the water's surface, confining a cylinder of air on top of a column of water. The water column rises and falls because of the waves, which compresses and decompresses the air column. This confined air is permitted to flow to and from the atmosphere through a turbine, which may normally revolve in either direction regardless of the airflow. The turbine's spin is utilized to create power.

2.5. Overtopping/Terminator Device

As shown in Figure **2e** the overtopping device collects ocean water from incident waves in a reservoir above the ocean surface. The water is subsequently discharged to the ocean via a typical low-head turbine that produces electricity. The low-head turbines are types of turbines that generate hydroelectric energy when the water's head is less than 20 meters, approximately [8]. To concentrate the wave power, the overtopping mechanism might additionally employ collectors.

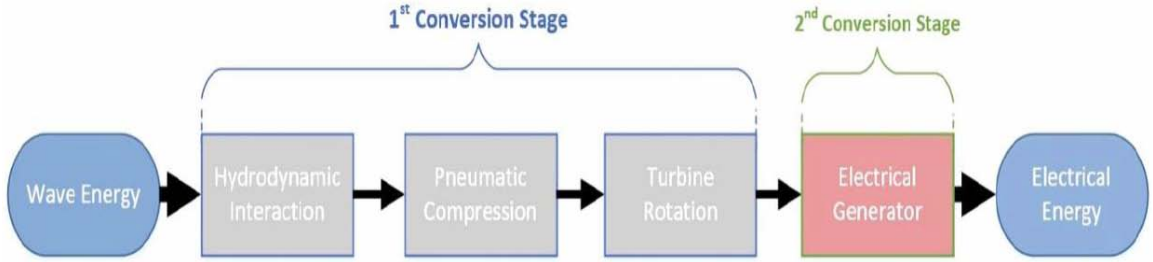


Figure 3: Processes for converting wave energy in an oscillating water column [14].

2.6. Submerged Pressure Differential

An illustration of the submerged pressure differential mechanism is shown in Figure **2f**. This type of WEC is a submerged point absorber that employs the pressure difference between wave crests and troughs above the system. It is made up of two primary parts: a fixed seabed air-filled cylindrical chamber and a mobile top cylinder. The water pressure above the equipment presses the air inside the cylinder as a wave crest passes over it, pushing the top cylinder down. The water pressure on the equipment (i.e., submerged pressure differential) decreases as a trough passes over it, while the higher cylinder lifts. This equipment has the benefit of not being vulnerable to the harmful knocking stresses experienced by floating devices, as well as having a lower visual effect.

2.7. Bulge Wave

Figure **2g** depicts the bulge wave technique, which comprises a water-filled rubber tube tethered to the seabed and oscillating in the waves. Water flows into the tube through the stern, and the incoming wave generates pressure fluctuations down the length of the tube, resulting in a 'bulge.' As the bulge moves down the tube, it gathers energy that can be employed to power a typical low head turbine at the bow from which the water is subsequently returned to the ocean.

2.8. Rotating Mass

Figure **2h** shows the schematic of a rotating mass device. Two types of rotation are employed to gather energy from the movement of the hemisphere (as shown in Figure **2h**) in the waves, surging and oscillating. Linear acceleration is caused by the motion of an uneven mass or a gyroscope. In both situations, the motion is linked to an electricity generator located within the equipment.

To create an overall perspective, the previous sub-sections provided a brief illustration of different categories of WECs. However, among the discussed classifications, this study focuses mainly on the OWC system.

3. OWC TECHNOLOGY

Yoshio Masuda, who developed a 120W OWC in Japan in 1965, was the first person to present using the OWC idea [13]. The OWC principle has also been employed in multiple varieties around the world, and it is preferred for its simplicity of operation with no immersed moving components, structural durability, convenience of maintenance, and adaptability to be employed in different situations.

Figure **3** depicts the fundamentals of the OWC energy conversion stages. As seen, two stages are essential for energy conversion. The first one is the conversion of hydrodynamic interaction into mechanical energy, in which the momentum of the waves pressurizes the air, which is used by the air turbine. The generator is then used in the second stage to convert mechanical power to electrical current [14].

The OWC idea harvests energy by employing waves' surface motion to compress the air inside a column. As shown in Figure **4**, the surface raises as the peak of the wave crosses and falls with the tunnel of the wave, creating bidirectional airflow and pressure variations within the cylinder. A turbine capable of accomplishing rectification by itself is necessary for these bidirectional airflow devices to allow for continued spinning in one path while the flow constantly changes direction past the turbine. The Wells turbine, developed by Prof. Alan Arthur Wells of Queens University, is the most frequently deployed turbine in OWCs [15]. This turbine solves the obstacle of alternating airflow rate using symmetric airfoils, which allow the turbine to spin in one direction independent of the airflow path. Additional turbine choices, including the self-rectifying bidirectional impulse turbine [16] and Savonious turbine [17], have been proposed and future developments in this field are being investigated.

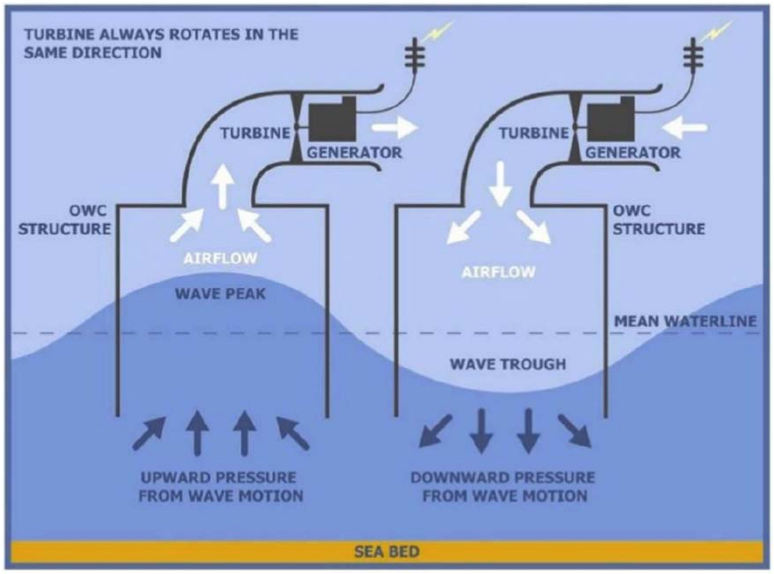


Figure 4: The main idea of OWC [15].

One major advantage for OWCs is that despite the method of harnessing the wave power, they can be deployed in different location in the ocean based on their design and structure:

- Integrated into breakwater (shoreline): one of the most common models which decreases the cost of deployment and maintenance
- Nearshore: can be deployed as an array of floating OWCs
- Offshore: with the ability to be integrated into the floating structures and buoys

3.1. Multi-Resonant OWCs

Most multi-resonant devices are self-tuning versions of the OWC concept meaning that they function effectively over a wider frequency band founded on the assumption that various lengths of the water column affect the resonant period of the OWC [18], with the moveable surface being the primary wave radiator. The Ocean Energy (OE) Buoy, based on the backward bent bend duct buoy concept is one example of an OWC multi-resonant device [19], with an L-shaped cylinder exposing the intake to the travelling wave, as shown in Figure **5**.

3.2. Multi-Oscillating Water Columns

The multi-oscillating water column (M-OWC) concept, also known as the multi-chamber oscillating water column [20], is a configuration of OWC installations that are connected in terms of construction, airflow, PTOs, or generators. However, one of the drawbacks of OWC functioning is the variable energy output caused by bidirectional airflow, which is the fundamental issue that more current M-OWC designs normally try to address. Although the self-rectifying turbine technique is well developed, it remains an ineffective phase in the energy conversion process, which gives the M-OWC a significant privilege.

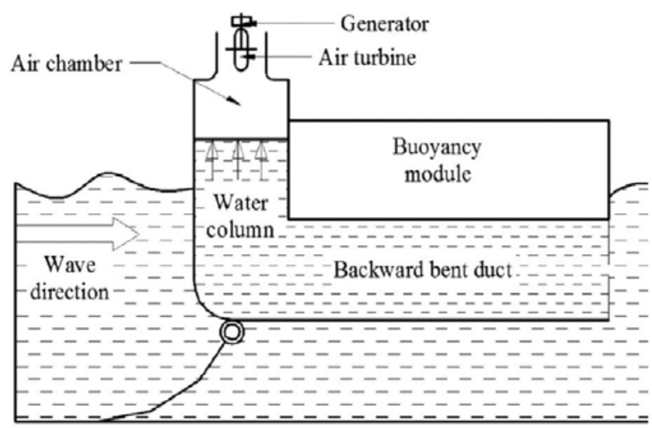


Figure 5: The schematic of a backward bent duct buoy [19].

It is critical to identify the three primary M-OWC sub-classes as reported by Delmonte *et al*. [14]. Figure **6a** shows an OWC array that comprises many unique OWCs that operate in solitary with separate turbines and generators but are placed in a shared framework to form one system. Figure **6b** depicts a segmented M-OWC for which the turbines of numerous OWCs stay separate but are structurally connected to run the same generator. Figure **6c** shows a modular M-OWC, which utilizes a series of cylinders that provide airflow that is

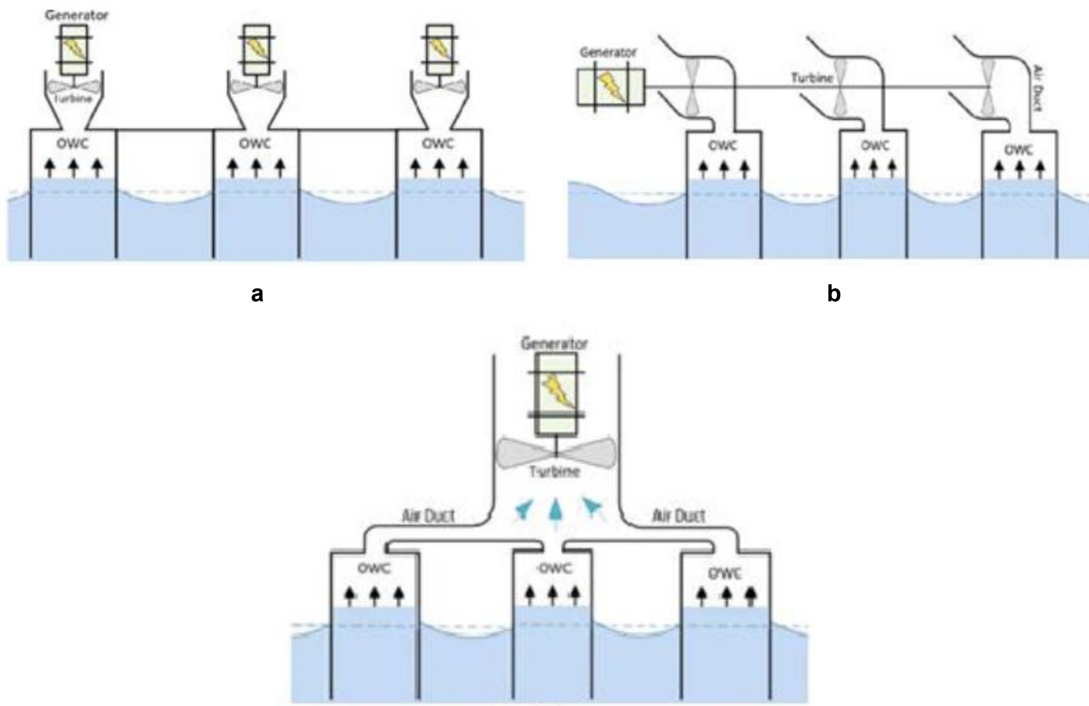


Figure 6: Multi-oscillating water columns: (**a**) OWC Array design; (**b**) segmented M-OWC design; (**c**) Modular M-OWC design [14].

coupled or collected and adjusted upstream of the turbine. As a result, the merging of the different OWC units happens prior to the PTO phase to provide continuous unidirectional airflow. The M-OWC could be extensively classified further into sub-groups, particularly the segmented or modular M-OWCs. Modular M-OWCs, for instance, can be open or enclosed devices. Closed devices generate large and small pressure channels downstream and upstream of the PTO, resulting in a significant pressure difference. As a result, a controlled volume of working fluid is in rotation. Open devices use large pressure upstream and ambient pressure downstream of the PTO.

When a device runs exclusively on unidirectional airflow, the process of inhaling and exhaling does not proceed throughout the entire system, as it does with a standard OWC. As a result, the phrases upstream and downstream relate to the distinct functioning situations, which is the constant directional variation of airflow [6].

3.3. Floating OWCs

A two-cylinder system called MORE was originally examined in a MARINET project [21]. It was based on the M-OWC Sea breath idea, which is shown in Figure **7**. Such a floating system is made up of numerous OWC cylinders aligned with wave propagation. As the wave tops and bottoms pass, each OWC generates large and small pressures. Unidirectional valves enable pressurized air from each cylinder to collect in a central high channel during the compression phase. Furthermore, unidirectional valves permit flow from the low-pressure channel to occupy the cylinder when the water content drops, resulting in negative pressure. The high and low-pressure channels, as shown in Figure **7** form a closed device with a theoretically more consistent high-pressure flow difference throughout the turbine. The benefit of these devices is that there will continuously be a consistent intake of air, even in less-than-ideal situations.

The LEANCON device [6] is a hovering V-shaped M-OWC that generates large and small pressure air channels using an array of various small OWC cylinders, as shown in Figure **8**. The 'V' shape, enables the WEC to collect a wider breadth of the wave. The huge quantity of cylinders, in theory, create an equilibrium of forces as localized peak and weak pressures act within the cylinders. The structure is small, with air channels incorporated into the structural construction and a PTO system consisting of turbines placed between peak and weak pressure channels according to unidirectional flow. The device's shape, as well as the collection of cylinders angled with their entrances facing the incident wave peak, are designed

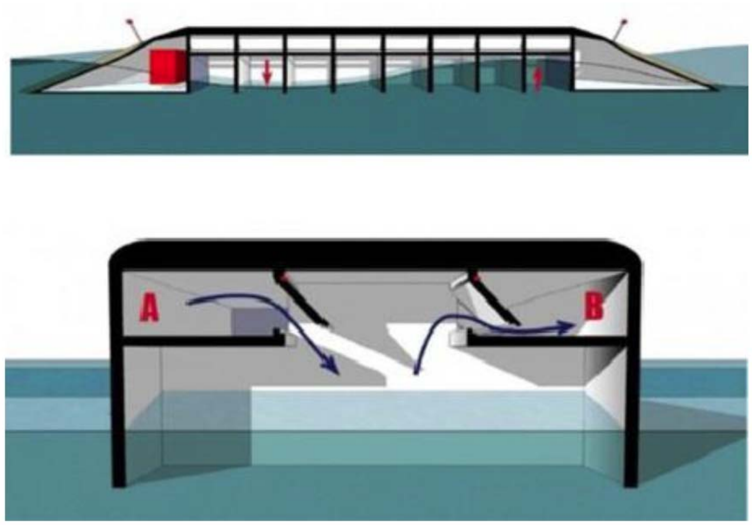


Figure 7: Sea breath device as the floating concept [21].

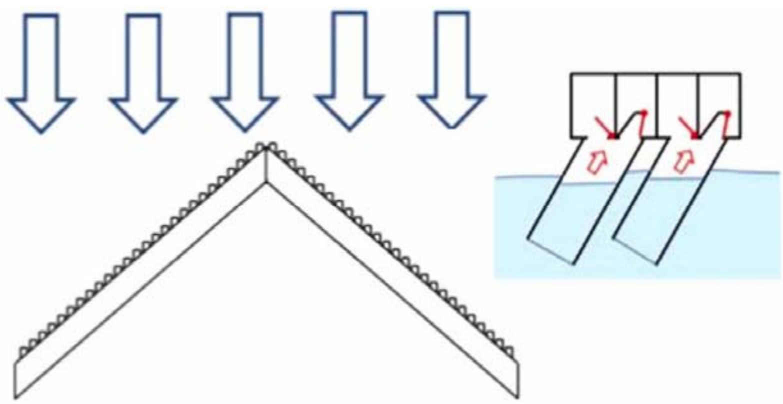


Figure 8: The orientation and working premise of LEANCON [23].

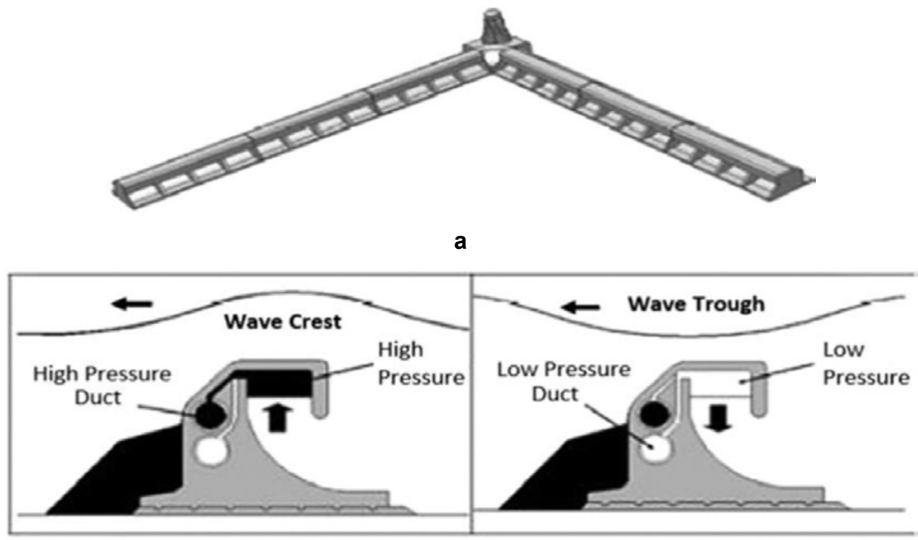
to reduce the wave force of impact. Additionally, the anchorage location, which is optimal when on the bow, aids the WEC in aligning with the wave axis, because the two arms create a stabilizing function [6]. The majority of OWCs are onshore or semi-immersed floating constructions, except for a fully submerged shallow sea, V-shaped breakwater incorporated converter [22]. This M-OWC type, which is installed on the seafloor, employs a closed cycle unidirectional airflow device comprising unidirectional valves and strong and small pressure connectors, as shown in Figure **9** (Stellenbosch equipment). When immersed, the chances of component failure reduce, but components are subjected to accelerated overall corrosion rates [22].

Recently, experimental works with a 1:25 magnitude immersed single cylinder prototype of the concept have shown a total conversion rate of 22%. The design is already being investigated for certain purposes and further improvement [24]. Despite this fact, the practical optimization of the SWEC is still under development [25].

3.4. Multi-Resonant M-OWCs and Multi-Function OWCs

Resonance and the ability to tune to resonance are appealing qualities in singular OWCs. While different M-OWC concepts can solve the airflow problem, if a larger bandwidth or the potential for more resonant peaks can be developed, the M-OWC concept will undoubtedly stand out [6].

The integration of the OWCs with floating wind turbine can be considered as a cost effective and promising solution to absorb more energy and reduce platform dynamic response. A novel hybrid concept was designed in [49] which was a validation in time domain against 1:50 scale model wave basin test data along with testing different Power Take Off models. Authors in [50] proposed a new sharing platform to reduce the



a

b

Figure 9: Stellenbosch equipment configuration and operation concept [22].

total Levelised Cost of Energy (LCoE) including for both maintenance and infrastructure cost. They offered a multi-purpose solution using a new OWC WEC integrated into a floating breakwater with the ability to enhance wave energy conversion specially for long period waves without increasing the volume size and moving parts.

OWCs are also capable of being integrated into floating breakwaters as authors in [51] introduced the multi-functional solution to extract more power and to protect the converter infrastructure. The hydrodynamic performance of the model was compared among the multi-purpose platform, the isolated array of OWC and floating breakwater. The results showed that the internal water movement can be beneficial for both energy extraction and wave attenuation.

3.5. Performance Comparison

According to the equipment performance comparison compiled by Babarit [26], the M-OWCs' effectiveness (i.e., the efficiency of power extraction) ratings do not demonstrate considerable increases over the singular OWCs such as the (OE) Buoy. OWCs are particularly economical with fixed oscillating wave surge converters (OWSCs) especially compared to different forms of WECs, as shown in Table **2**. With only a few highly inconsistent performances of small-scale M-OWCs, it is difficult to say if they will be economical at this level. The modular type M-OWC capabilities and estimations have been insufficient to remain competitive with various singular OWCs. The CWR data summarized by Babarit [26] and shown in Table **2** effectively provides the evaluations and demonstrates that for OWCs, like with other WEC categories, no equipment functionality considerably surpasses the others.

In this Section, the various categories of the OWC system have been illustrated in more depth since it will be the focus of the study. Moreover, the reasons for choosing OWC among several types of WECs to study in this study have been discussed.

4. INTEGRATED OWC AND BREAKWATER STUDIES

Practically, there are two methods to reduce the cost of the OWC device's wave power. One is to increase the

Table 2: Mean and Standard Deviation of Capture width Ratio (CWR) for Different WEC Categories [26]

Property	Approach	OWCs	Overtopping devices	Heaving devices	Fixed OWSCs	Floating OWSCs
Capture width ratio (%)	Mean	29	17	16	37	12
	STD	13	8	10	20	5
Characteristic dimension(m)	Mean	20	124	12	18	33
	STD	10	107	7	14	24

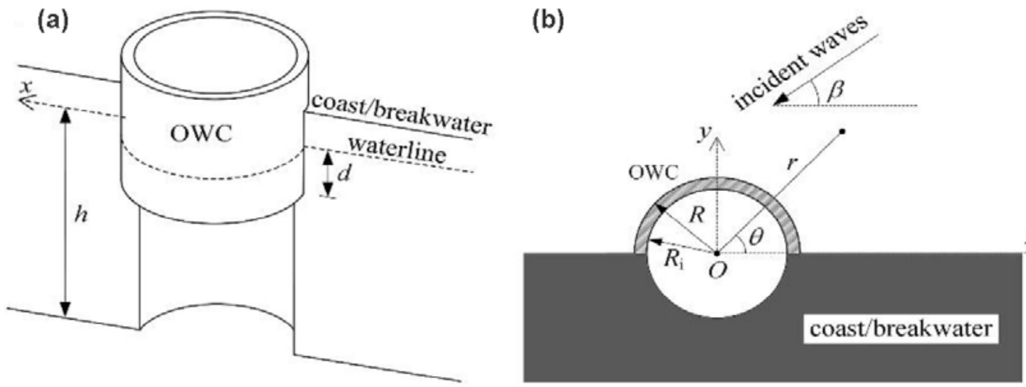


Figure 10: OWC incorporated into a coast/breakwater: (**a**) bird view; (**b**) top view [32].

effectiveness of the wave power harvesting system directly using a sequence of optimization procedures, while the other one is to incorporate the OWC system into a novel marine construction. Many scholars have conducted analytical studies on the incorporation of an OWC into a breakwater. The hydrodynamic properties of a two-dimensional OWC, consisting of a narrow vertical surface-piercing obstacle beside a perpendicular wall were investigated by Evans *et al*. [27]. The theoretical results that were presented showed that an OWC could recover all the input wave power due to wave reflection from the wall. Rezanejad *et al*. [28] analysed the effectiveness of a 2D dual-chamber nearshore OWC. The intake of the outer chamber had been discovered to be vital in setting the main resonance frequency, which benefited overall electricity production. Ref. [29] investigated the influence of stepped lower part topography on the effectiveness of a 2D nearshore narrow-wall OWC and concluded that the introduction of an artificial step at the seabed, together with some adjustment, results in a greatly improved capacity of energy extraction for electricity generation.

Martins-Rivas and Mei [30, 31] studied the behaviour of a narrow-wall OWC placed at the point of a thin static breakwater or alongside a straight coastline, developing theoretical methods based on the linear potential flow concept to handle three-dimensional wave radiation challenges. An integral equation for the horizontal velocity under the wall was used in their simulations to account for the singular behaviours in the velocity field along with the void under the thin wall of the OWC cylinder. The retrieved energy of the OWC erected at the point of a narrow breakwater had been proven to be unresponsive to incident wave path, while the response of an OWC located on a straight coast was shown to be completely reliant on wave path for a range of frequencies, the greatest result obtained when the incidence was normal. The energy absorbed by the OWC can be doubled due to wave reflection at the coastline.

Zheng *et al*. [32] established a theoretical framework of a coast-breakwater integrated OWC that took into account the impact of the thickness of the OWC cylinder wall. Figure **10** shows their investigated system. Their result proved that the thinner the cylinder wall, when applied to a constant outer radius, the greater and wider the prominent peaks of the frequency response of wave energy catch width.

4.1. Arrays of OWCs Studies

The ultimate objective of studying OWC systems is to provide power on a large scale. Therefore, it is important to analyse the performance of the arrays of OWC systems, which is investigated by several scholars. Wave farms comprising arrays of OWCs are anticipated to be developed to completely capture the potential wave energy in a location and produce substantial amounts of electricity for power grids. Cost-sharing advantages of deployment and electricity supply transmission can also be achieved for those OWCs deployed close to each other. Nihous [33] provided a methodology to forecast wave energy absorption from an array of OWCs based on analytical analysis of hydrodynamic concerns from an oscillating circular patch on the ocean surface. Further, diffraction effects were ignored in the analysis. Nader *et al*. [34] used a 3-D finite element (FE) technique modelling to analyse a limited array of stationary OWCs without the limitation of shallow draught. The array's complicated hydrodynamic relationships with the OWCs were emphasized. Moreover, Figure **11** shows the overall wave magnitude surrounding and within the four OWC equipment arrays for different values of spacing.

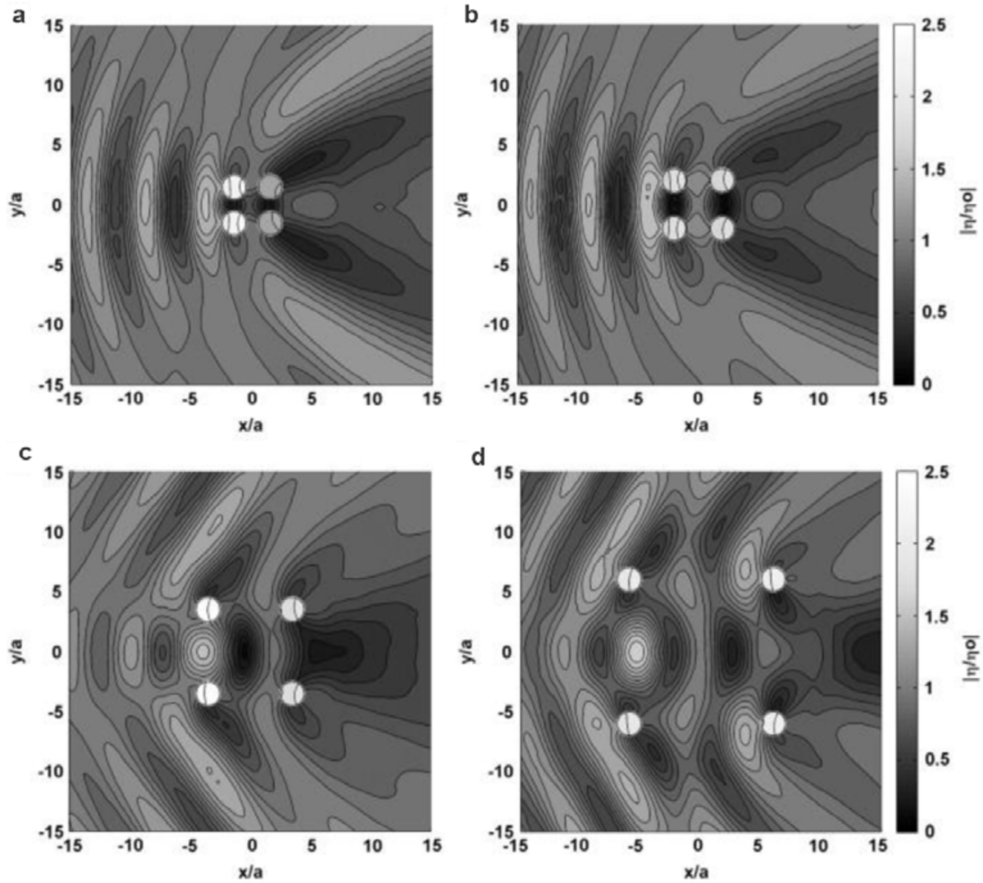


Figure 11: Overall wave magnitude surrounding and within the four OWC equipment arrays for different values of spacing (**a**) L/a=1, (**b**) L/a=2, (**c**) L/a=5, and (**d**) L/a=10 [34].

Subsequently, a more comprehensive simulation that took into consideration the air compressibility within the OWC cylinder was presented [35-37]. The results demonstrated that for specific wave frequencies, the array of stationary OWCs can capture more energy than the same number of OWCs working standalone. Konispoliatis and Mavrakos [38] designed an optimal analytical method to evaluate the behaviour of an array of floating OWCs. Significant enhancements in retrieved electricity were observed for arrays with specific distances between OWCs. An offshore dual-chamber OWC system subjected to frequent waves has been investigated by Ning *et al*. [39], experimentally as shown in Figure **12**. For the dual-chamber OWC mechanism, two distinct resonance frequencies were discovered.

4.2. Computational Fluid Dynamic (CFD) Studies

WECs account for a small but theoretically important portion of the world's renewable energy sources. Nevertheless, to compete with offshore wind or solar energy, the WEC sector will need to develop successful prototypes that can be scaled up for commercialization purposes. To reliably evaluate performance indicators during the primary design phases, this approach necessitates the implementation of effective and trustworthy numerical modelling methods. The computational fluid dynamic (CFD) algorithms that solve the Navier-Stokes equations or the Reynolds averaged Navier-Stokes (RANS) problems provide the treatment of complicated nonlinearities that other approaches cannot manage. The linear and nonlinear potential flow approach, fully nonlinear potential flow approach, and CFD method, which solves the Navier–Stokes equations for single-phase or two-phase fluids, are the three most used procedures for numerical modelling of WECs. The most challenging problem with the CFD approach is accurately resolving the two-phase fluid interface within the chamber between the water and air. Horko [7] used an experimentally verified two-dimensional CFD simulation using the Fluent software to evaluate the impact of the OWC chamber's frontal lip on the device's hydrodynamic behaviour. Ref. [7] discovered that modest adjustments to the chamber's frontal wall, such as increasing its thickness or giving curving, can result

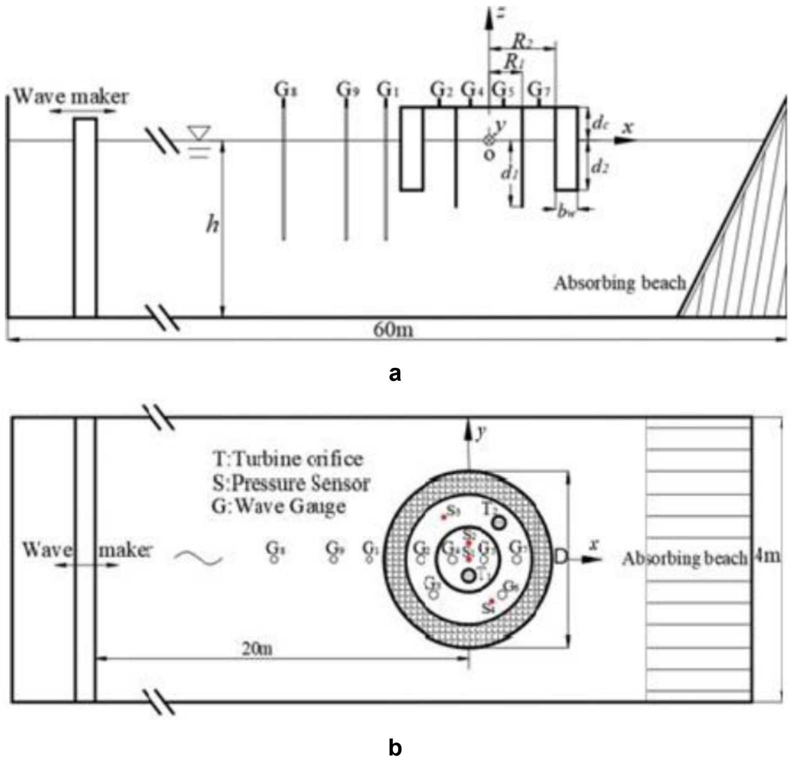


Figure 12: Experiment arrangements. (a) A side view of the OWC device and wave gauges; (b) a plan view of the orifices and pressure sensors [39].

in significant gains in OWC effectiveness. Using Navier-Stokes equations, Xu *et al*. [8] developed a three-dimensional CFD model to study the hydrodynamics of a circular bottom-sitting OWC mechanism demonstrating that vortex shedding significantly increases spatial distinctness within the OWC cylinder. Figure **13** shows a three-dimensional representation of the OWC simulation and wave height patterns within the OWC cylinder presented by Xu *et al*. [8].

Ref. [9] introduced an incompressible three-dimensional CFD method to evaluate the stationary multi-chamber OWC equipment. The CFD findings are proven to be consistent with the experimental results.

Goeijenbier *et al*. [40] study the opportunities for structural optimization to further reduce the costs of OWCs. In a one-way linked hydraulic-structural numerical simulation, an OWC with an extra vertical channel is studied in a three-dimensional domain. The model included a fluid domain, which was the wave tank, as well as a solid domain, which was the OWC structure. It was discovered that by removing the structural domain and utilizing the discovered property that water pressures are uniform across the crosswise width, a 2D model would be acceptable for feasibility study applications, which significantly reduces simulation complexity. Figure **14** depicts their results with the top row at the maximum inflow and the bottom row at the maximum outflow.

Wang and Zhang [41] carried out the numerical investigation of the hydrodynamic properties of an OWC mechanism linked with a submerged horizontal sheet using the CFD toolbox OpenFOAM. For an ideal structural design, the effects of changing the submerged depth and sheet length on relevant factors of a sheet-integrated device, such as energy absorption efficiency, reflection and transmission coefficient, and energy dissipation coefficient, were investigated. Furthermore, in terms of hydrodynamic characteristics and vorticity field, the unique WEC-sheet integrated system was compared to an OWC device positioned over an immersed breakwater at the same submerged level. The findings reveal that integrating a submerged horizontal sheet can significantly enhance the functionality of an OWC system and that a lesser submerged depth is far more able to achieve a fair transmission coefficient and be more advantageous for power production.

Elhanafi *et al*. [42] employed a nonlinear two-dimensional RANS-based CFD simulation to analyse

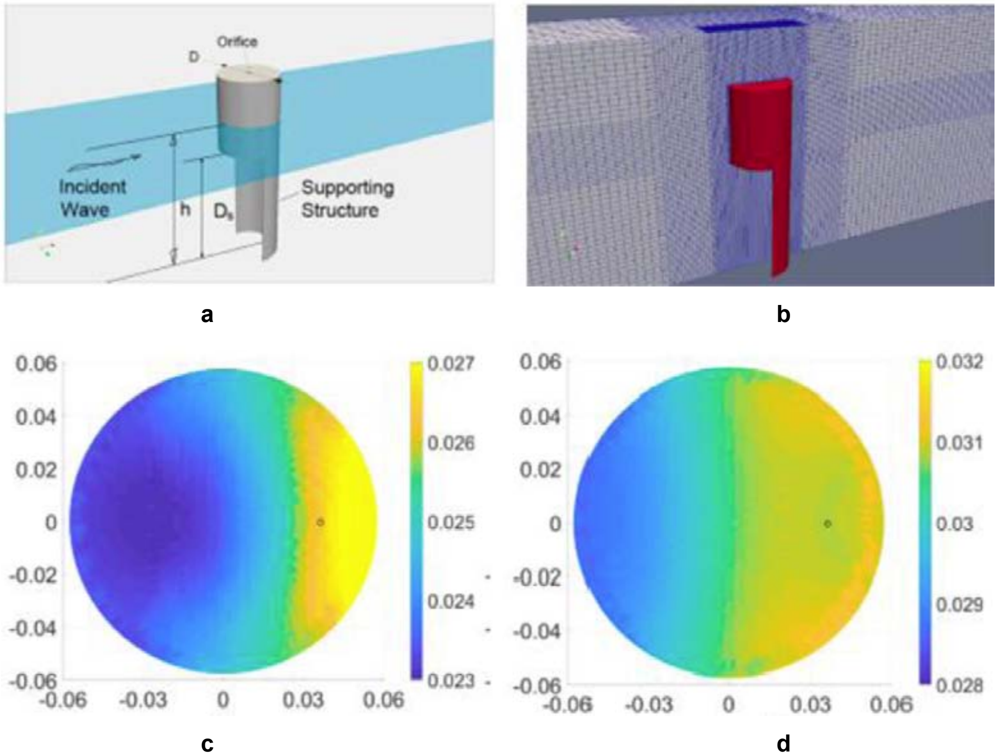


Figure 13: (**a**) a three-dimensional representation of the OWC simulation, (**b**) a perspective of the mesh setup around the OWC model (**c**) wave height patterns within the OWC cylinder for 0.7s time passed (**d**) wave height patterns within the OWC cylinder for 0.8s time passed [8].

the power equilibrium of an onshore OWC. The CFD simulation was validated using available physical data of cylinder differential air pressure and free surface level. It was discovered that the dampening used has a major influence on the energy conversion operation. Additionally, during the inflow and outflow stages, both power take-off (PTO) damping, and wave height have an essential impact on vortex generation near the top and bottom cylinder mouths.

Lopez *et al*. [43] propose an extensive simulation of the impact of seabed morphology on the efficiency of OWCs. Different wave parameters, notably storm and post-storm situations, are studied. The simulation model was defined in ANSYS Fluent, and the variations in the seafloor for various wave situations were simulated. Their results reveal that the performance of energy extraction in the OWC is strongly controlled by the seabed equilibrium states associated with storm development. Figure **15** depicts their results for the mass transport for the different scenarios. As observed, Figure **15** illustrates the normal development of a storm: strong waves (H=4m) with flat seabed (case γ shown in Figure **15**), proceeded by seabed development (case P8B shown in Figure **15**) with the same wave situations. Following that, with that developed seabed (case β shown in Figure **15**), a decrease in wave energy (H=2m), followed by a depletion in the dimension of the seabed morphology under the same moderate wave situations (case P4B shown in Figure **15**).

Cabral *et al*. [44] investigate the efficiency of a novel hybrid WEC module integrating an OWC and a piece of overtopping equipment incorporated into a rubble mound breakwater, based on outcomes of a physical model study carried out at a geometrical ratio of 1:50, as shown in Figure **16**. Before the experimental measurements, the device's effectiveness was numerically refined using ANSYS Fluent. The hybrid WEC's wave power capture was computed, and the efficiency of the two capturing approaches was examined. It was proved that hybridization could result in technologies that are more efficient than their single components for a wider variety of wave circumstances.

For three-dimensional modelling of an OWC, a novel solution for wave and structure interaction is employed by Iturrioz *et al*. [10]. The RANS equations for two incompressible phases are solved using the CFD simulation, which was water and air. To verify the numerical findings, laboratory tests are conducted on a modest scale. The method is also used to better

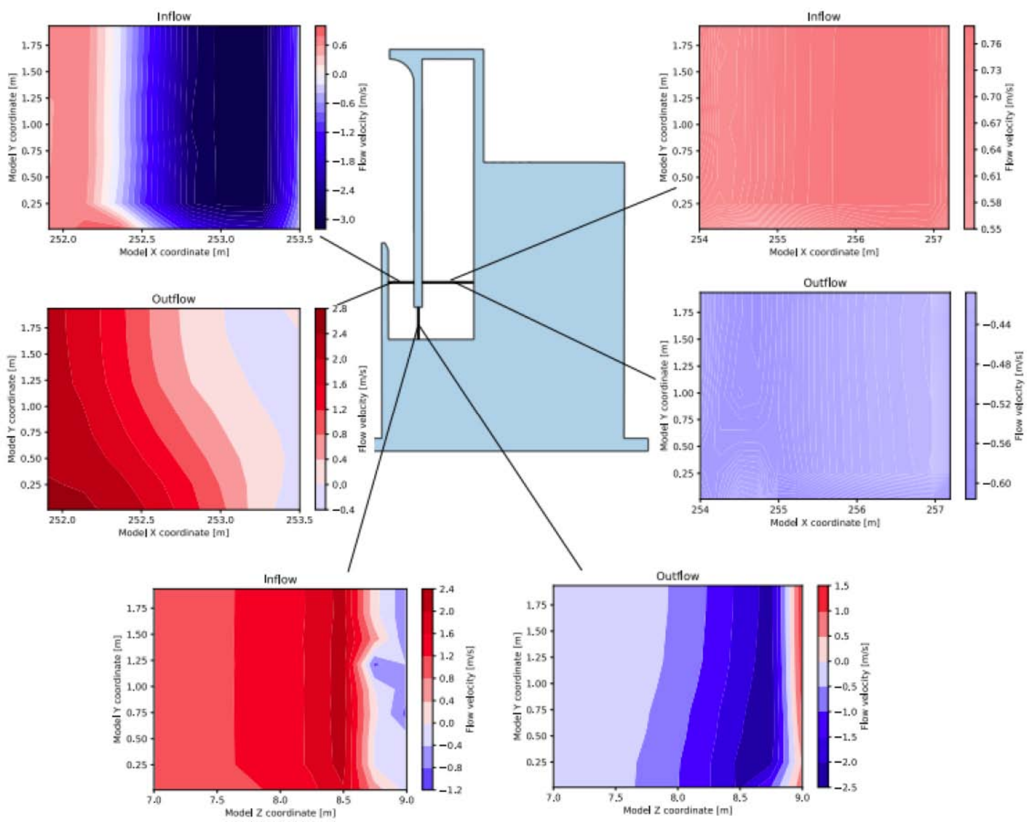


Figure 14: Flow velocity pattern in the channel at maximum outflow and inflow, beneath the front wall, and within the cylinder [40].

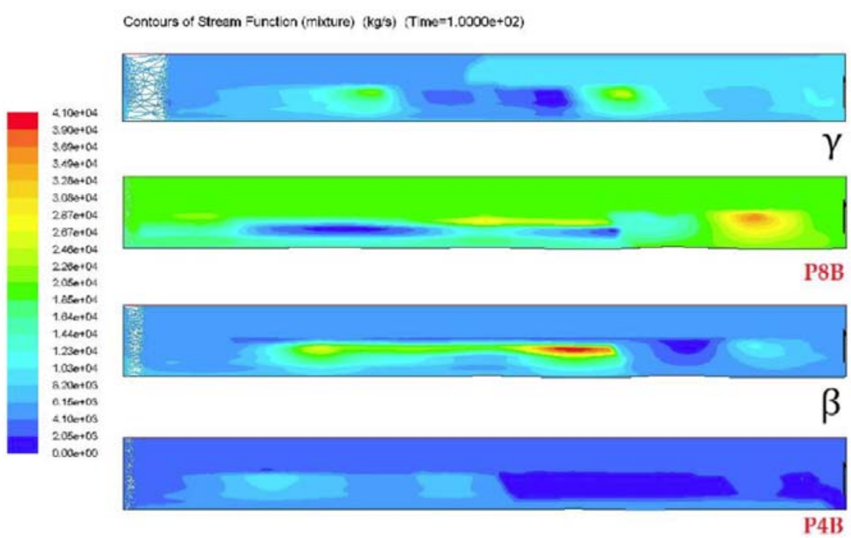


Figure 15: Stream contours of velocity (kg/s) for different scenarios [43].

awareness of important mechanisms and demonstrates the possibilities for extensive investigation. Even though the experimental situation was two-dimensional, the three-dimensional field of the wave flume was numerically modelled to demonstrate OpenFOAM's potential. Figure **17** depicts CFD results achieved by Iturrioz *et al*. [10] for airflow velocity as time passes.

4.3. Hybrid Wave-Wind Studies

Wind and wave behaviour are inextricably related. As a result, the design of hybrid technologies should be the next stage in the growth of the ocean renewable industry [15]. Hybrid developments integrate floating wind turbines with WECs to harvest energy from the

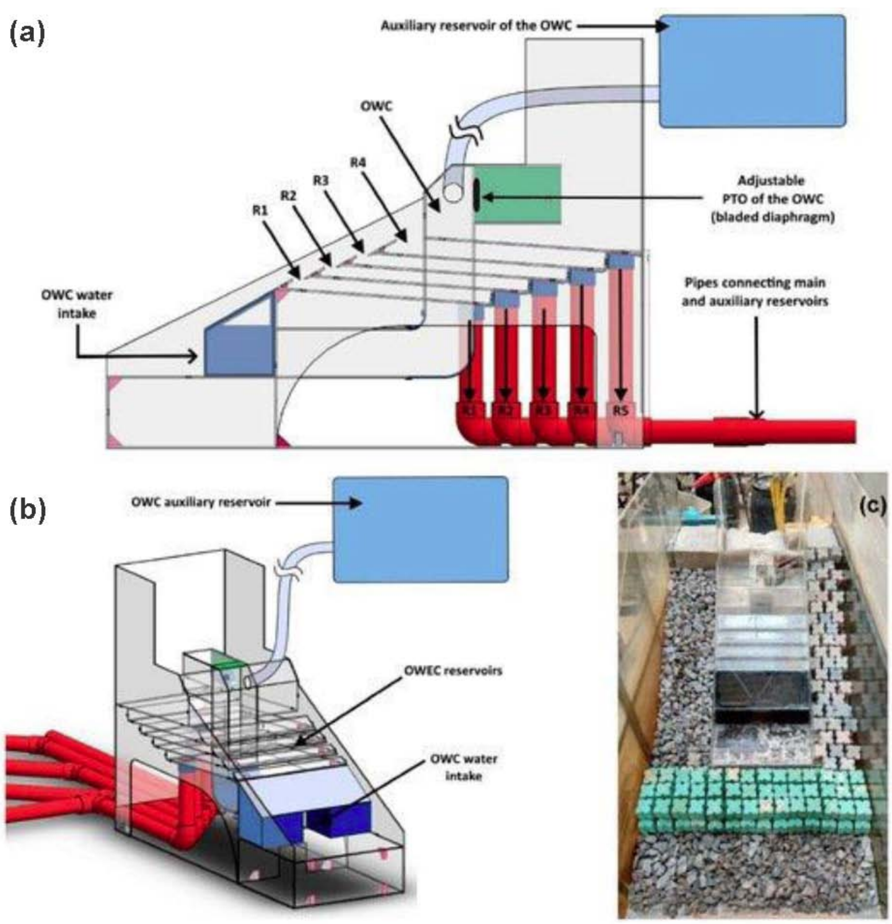


Figure 16: (**a**) Cross-section picture; (**b**) three-dimensional image of (**c**) the planned physical design with HWEC positioned in the centre of the breakwater during the Antifer blocks armour surface installation [44].

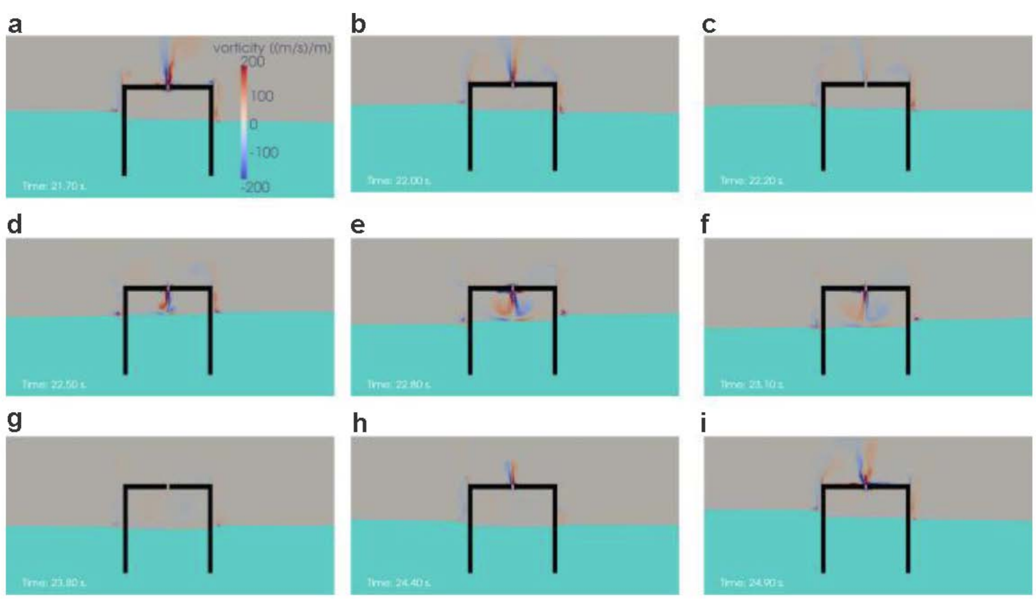
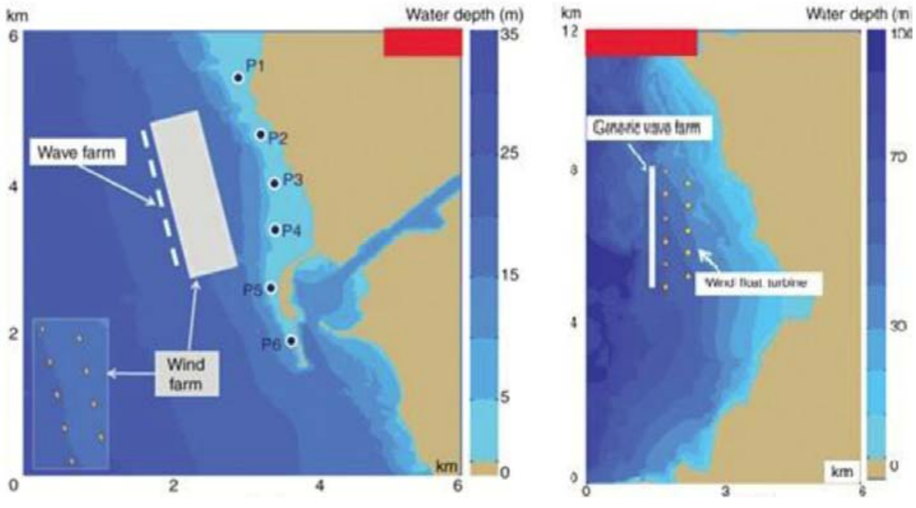


Figure 17: Airflow vorticity during a chamber pressurization-depressurization loop as time passes: (**a**) t=21.70 s; (**b**) t=22.00 s; (**c**) t=22.20 s; (**d**) t=22.50 s; (**e**) t=22.80 s; (**f**) t=23.10 s; (**g**) t=23.80 s; and (**h**) t=24.40 s; and (**i**) t=24.90 s [10].

offshore region while reducing initial costs. In this classification, current or existing harbour equipment could create hybrid technologies that combine electricity generation and harbour safety.



a b

Figure 18: Integrated wind and wave system scenarios have been described for a variety of coastal ecosystems, including (**a**) Leixoes (Portugal) [46] and (**b**) Porto Ferro (Sardinia) [47].

A novel integrated approach for the multi-application usage of offshore renewable energy resources that consists of an OWC device and an offshore wind turbine is developed in [45]. A monopile structure supports the wind turbine, and the associated OWC is concentric with the structure. The external shell of the OWC and the monopile structure are joined within the cylinder by four vertical reinforcing sheets. The outcomes show that by selecting an ideal turbine setting, wave power generated by the OWC can be a valuable complement to the integrated system. Furthermore, in certain wave situations, the wave forces on the OWC and the monopile can neutralize each other, resulting in an almost zero net wave force on the entire structure.

Figure **18** [46, 47] depicts two case studies in which the influence of various wind-wave developments on the regional wave system was assessed. The research revealed that the shadow impact might be influenced by parameters such as wave path, the spatial alignment of the marine field, coastline, wave strength, and the farm's absorption capacity. To protect a specific beach area, it is necessary to initially evaluate the regional wave behaviour and then determine an appropriate WEC layout, considering the chain consequences that may arise in nearby coastline regions.

5. RESEARCH OPPORTUNITIES AND METHODOLOGY

The research model introduced by [42] the hydrodynamic performance of an OWC device and performed energy balance analysis to explain the energy conversion chain for an OWC using a CFD model and results validated against a practical model designed by [48]. Figure **19** shows the detail of the numerical model used in [42] including the dimension of the numerical model and the position and structural details of the designed fixed OWC.

As mentioned before, chamber differential air pressure and airflow rate inside the orifice are the two most factors that can simulate the achievable output power from an OWCs. The main factor which has a direct effect on the air pressure inside the chamber of an OWC is the free surface movement inside the chamber which compresses and decompresses air inside the chamber. A 2D CFD model was designed to validate the airflow, air pressure and output power with the practical experiment in [48] with an error of less than 0.5% which shows the high capability of the CFD model in modelling practical experiments.

The objective of the practical experiment in [48] was to perform an analysis of the influence of the main environmental parameters like wave conditions on OWC hydrodynamic performance. The authors performed 387 tests under different wave conditions and tidal waves, and they found that turbine damping has the most effect on the hydrodynamic performance of an OWC, so, selecting the right turbine is necessary to have the OWC in optimal working condition. This practical model is set up in a flume tank at the University of Santiago de Compostela, which was 20 m long, 0.65 wide and 0.95 high.

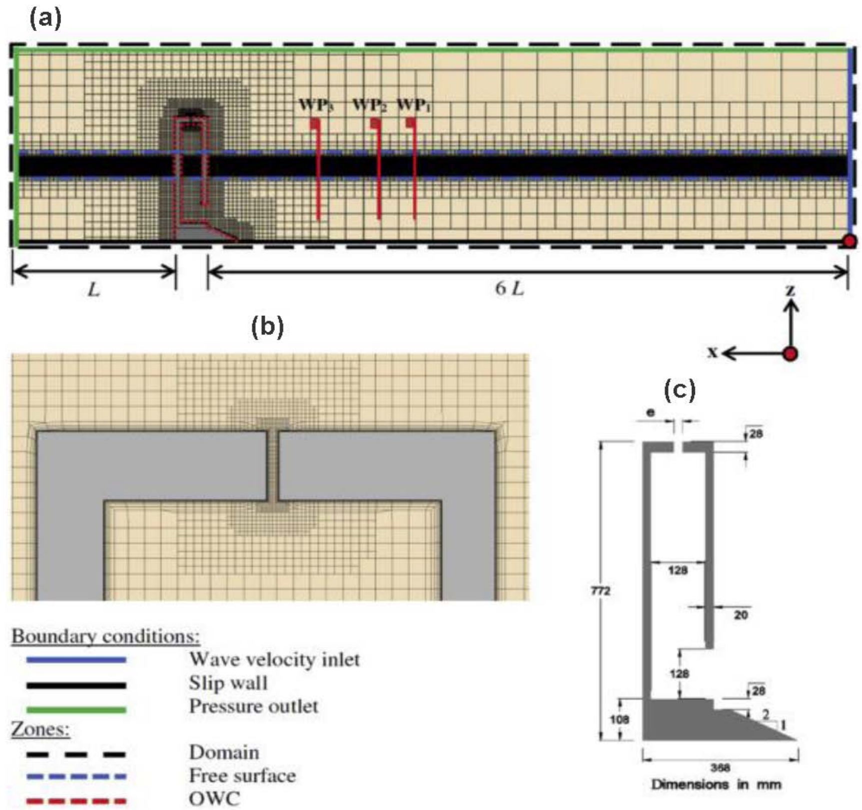


Figure 19: Concept design parameters and mesh details with the dimension details for the fixed OWC in [42].

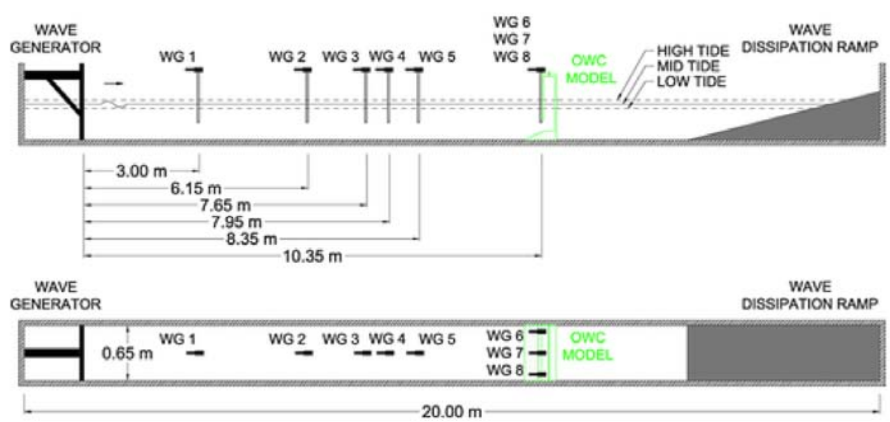


Figure 20: Detail of the experimental design including the placement of the sensor positioned along the tank in [48].

Waves are generated using a piston-type paddle which shows as the Wave Generator in Figure **20**. Eight gauges are positioned along the tank and OWC to measure the wave height along the tank and inside the chamber of the OWC. Table **3** explains the details of the practical design of the experiment in [48] including the detail of the converter and flume tank. Pressure and ultra-sonic sensor are used to measure the differential air pressure between the chamber and outside. The same model for flume tank and measurement elements are designed in [42] as shown in Figure **21**.

Most recent studies on OWC systems are described in Table **4**. As presented, despite prior studies' accomplishments, considerable research opportunities remain undiscovered as in the followings:

- A substantial majority of studies have not considered a progressive evaluation of the two-phase interaction of air and water throughout the simulation procedure for OWC WECs.
- Many studies have ignored a comprehensive analysis to account for the effect of incorporating

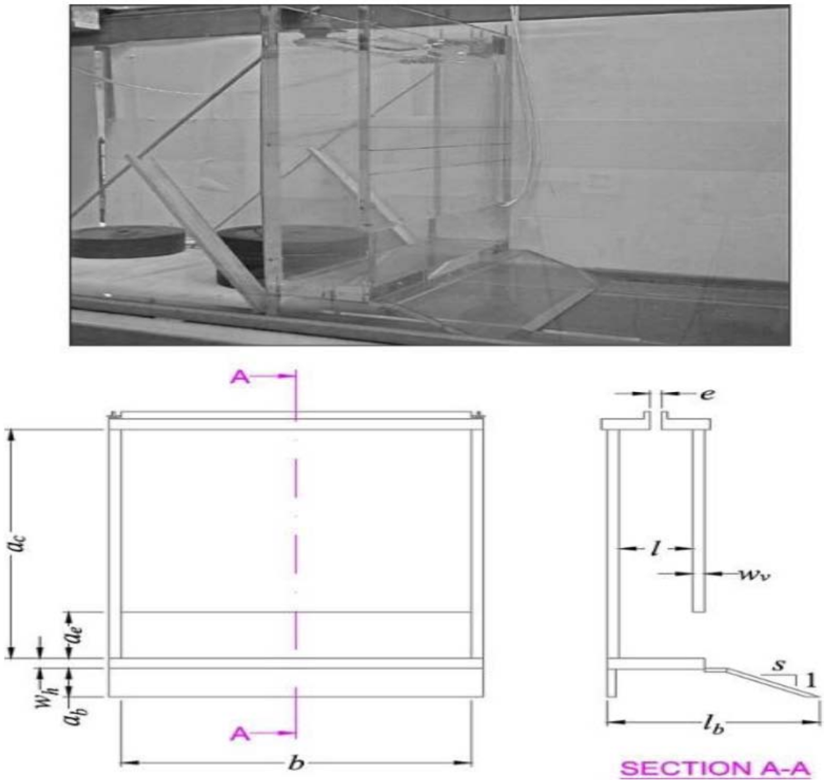


Figure 21: Fixed OWC employed in [48] with dimension details for orifice and chamber.

Table 3: Dimension Details of the Practical Model Used in [48]

Geometrical details	parameter	Dimension (m)
Chamber height	a_c	63.6×10-2
Chamber width	b	60.8×10-2
Chamber length	l	12.8×10-2
Entrance height	a_e	12.8×10-2
Horizontal wall thickness	W_n	02.8×10-2
Vertical wall thickness	W_v	02.0×10-2
Bedding height	a_b	08.0×10-2
Bedding length	l_b	36.8×10-2
Bedding slope	s	2

wind energy into the OWC construction in terms of increasing airflow velocity through the turbine blades.

- Although the use of a structure like windcatchers for increasing thermal comfort was recently studied by a few researchers, none of them investigated the effect of employing the windcatchers arrangement on the OWC system performance. Besides, the advantage of using a two-sided design of windcatchers is ignored in these systems.

- To achieve the best system performance, the proposed system should be evaluated in terms of airflow control. Previous research, on the other hand, did not suggest a novel turbine placement to manage both the airflow produced by compressed air in the cylinder and the wind flow provided by the windcatcher's entry.

Referring to Table **4** and the discussed research gaps, the main objectives of the literature review has been presented in this paper.

Table 4: List of Recent Studies on the OWC Systems to Find the Research Gaps

Study	Year	Brief description	Was the two-phase interaction of air and water are considered throughout the simulation procedure?	Was the effect of incorporating wind energy into the OWC construction examined in terms of increasing airflow velocity through the turbine blades?	Was the effect of using the windcatcher on the system performance investigated?	If so, was a two-sided design of windcatchers presented?	Was a novel turbine placement designed to control the airflow produced by pressured air in the cylinder as well as the wind flow provided by the windcatcher's entrance?
Horko [7]	2007	An experimentally validated two-dimensional CFD simulation using the Fluent program to assess the effect of the OWC chamber's frontal lip on the device's hydrodynamic performance.	No	No	No	No	No
Martins-Rivas and Mei [30]	2009	They investigated the behaviour of a narrow-walled OWC positioned at the tip of a thin static breakwater or alongside a straight shoreline, developing theoretical approaches based on the linear potential flow idea to deal with three-dimensional wave radiation difficulties.	No	No	No	No	No
Nader *et al*. [34]	2012	A three-dimensional finite element (FE) technique to examine a small array of stationary OWCs without the constraint of shallow draught.	No	No	No	No	No
Rezanejad *et al*. [29]	2013	They investigated the efficiency of a 2D dual-chamber nearshore OWC.	No	No	No	No	No
Iturrioz *et al*. [10]	2015	The CFD simulation was used to solve the RANS equations for two incompressible phases, which were water and air.	Yes	No	No	No	No
Elhanafi *et al*. [42]	2016	A nonlinear two-dimensional RANS-based CFD modelling to examine the power equilibrium of an onshore OWC.	Yes	No	No	No	No
Xu *et al*. [8]	2019	A three-dimensional CFD analysis was used to investigate the hydrodynamics of a circular bottom sitting OWC system.	No	No	No	No	No
Shalby *et al*. [9]	2019	A three-dimensional incompressible CFD approach for evaluating stationary multi-chamber OWC technology	No	No	No	No	No
Lopez *et al*. [43]	2019	A thorough simulation of the effect of bottom morphology on OWC efficiency.	Yes	No	No	No	No
Cabral *et al*. [44]	2020	Investigation of the effectiveness of a specific hybrid WEC module that incorporates an OWC and a piece of overtopping equipment into a rubble mound breakwater	No	No	No	No	No
Goeijenbier *et al*. [40]	2021	In a three-dimensional domain, an OWC with an extra vertical channel is explored using a one-way connected hydraulic-structural numerical modelling.	Yes	No	No	No	No
Wang and Zhang [41]	2021	A numerical analysis of the hydrodynamic parameters of an OWC mechanism coupled with a submerged horizontal sheet employing the CFD toolbox OpenFOAM.	Yes	No	No	No	No

6. CONCLUSIONS

In this paper a detailed research gap analysis to comprehend the up-to-date direction in the field of WECs and OWCs was conducted. Various OWC WEC and hybrid wind-wave studies are included with merits and demerits for each one. The study shows that there are still a wide range of opportunities in optimising the structure of OWCs, different ways of deployment and multi-function OWCs and new ways of harnessing the wave and wind using this technology. In addition, it has been shown that the OWC WEC is one of the simplest forms of capturing the wave energy with less moving parts and less complexity and ability to be integrated to other WECs or even other renewable energy technologies like wind turbine. The purpose is to provide a researcher a clear picture of the best method that should be chosen to implement his/her project.

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