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Advancement of Oscillating Water Column Wave Energy Technologies through Integrated Applications and Alternative Systems

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Abstract**—**Wave energy converter technologies continue to show good progress in worldwide research. One of the most researched technologies, the Oscillating Water Column (OWC), is arguably one of the most popular categories within the converter technologies due to its robustness, simplicity and versatility. However, the versatility of the OWC is still largely untapped with most deployments following similar trends with respect to applications and operating systems. As the competitiveness of the energy market continues to increase, the demand for wave energy technologies to be innovative also increases. For existing wave energy technologies, this requires identifying areas to diversify for lower costs of energy with respect to applications and synergies or integrated systems. This paper provides a review of all OWCs systems integrated into alternative applications in the past and present. The aspects and variation in their design, deployment and system operation are discussed. Particular focus is given to the Multi-OWCs (M-OWCs) and their great potential to increase capture on a larger scale, especially in synergy applications. It is made clear that these steps need to be taken in order to make wave energy a competitive and viable option in the renewable energy mix as progression to date shows that stand alone single function devices are not economical. Findings reveal that the trend of development is moving toward these integrated applications in order to reduce the Levelised Cost of Energy (LCOE) and will ultimately continue in this direction in efforts to make wave energy a competitive option in the renewable energy mix.

Keywords**—**Ocean energy, wave energy, oscillating water column, renewable energy, review.

I. INTRODUCTION

OCEAN renewable energy remains to be one of the world's largest untapped energy sources. In current political circumstances with the challenge of fighting climate change, greater attention will inevitably fall upon all forms of renewable energy as the pressure builds to increase overall capacity of the renewable energy mix. Compared to other forms of renewable energy and even ocean renewable energy, wave energy is still in its infancy despite the decades of research and development. Many Wave Energy Converters (WECs) have been patented and tested; however, few have progressed onto large scale testing resulting in a lack of convergence in technology across all types and subtypes of WECs. Although progress has been slow with respect to other renewables, due to the significant challenges involved, wave energy remains a very attractive prospect due to the potential of wave energy, in the UK alone, which is estimated to be between 250 and 600 TWh/year [1].

There are a wide range of great challenges that face WEC development, deployment, operation and maintenance. However, these can vary between technologies and therefore vary the overall costs. Often WECs are categorized by their operating principles and a major of these categories is the OWC, which is very popular and makes up a high percentage of the overall deployed devices. In literature there are several in depth reviews on WEC technologies and their deployment status [1]-[7].

The versatility of the OWC concept is still largely untapped with deployment characteristics with respect to operational characteristics and applications being similar. As discussed in this paper, the versatility of the OWC is increasing within research in recent years and is such that many subcategories have developed from this operating principle. Often this versatility and diversity is achieved with M-OWC concepts. This includes innovative concepts that not only scale up energy production and potentially performance, but also find other means to reduce the additional costs that currently make wave energy a less viable option. This involves deployments of large-scale wave farms, synergy projects or pre-existing integrations. The M-OWC, in general, generates opportunity for a wide range of different applications and variations in synergy projects. Identification of these innovative and cross sector beneficial technologies alternative applications and synergies are required in order to transform wave energy prospects as a competitor and a feasible option for commercial deployment.

Naturally, the second area of focus for this paper leads into the review of developments and improvements in an area of great disadvantage with OWC technology, the Power Take-Off system (PTO). This challenge is due to the bidirectional airflow created by the OWC at a very slow frequency. This paper does not concern the finer details of turbine technology but rather the PTO system as a whole and the development of the different types of PTO systems over the years. Hence, optimization of turbines is not discussed, but variations of designs are mentioned and variations in systems are discussed.

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II. THE OSCILLATING WATER COLUMN

A. History and Background

The OWC concept essentially involves a structure either floating or fixed, with semi-submerged open-bottom chambers containing volume of air. As the internal free surface oscillates like a piston within the semi-submerged chamber, bidirectional air flow is generated due to the pressure drop, which is created and constantly changing with the displacement of the free surface. Hence, the OWC wave-to-wire energy conversion process is made up of two major stages. The conversion from the hydrodynamic interaction of the wave into pneumatic compression, which rotates the air turbine or PTO, is considered the first stage. This mechanical power is then used to create electrical energy in the second major stage with an electrical generator. The first major stage can be further divided into processes, which entail the conversion of wave power into the hydraulic power of the free surface in the chamber.

The OWC concept is by no means a new concept for generating energy from the waves. In Japan, in 1965, Yoshio Masuda implemented the OWC to power a fairway and weather buoy rated at 70 W and 120 W respectively [8]. In 1978, Masuda then scaled up the OWC concept with a commercial-size M-OWC device known as Kaimei [9]. Since then, a number of other OWC prototypes have been deployed for research purposes in Japan and around the world; for example, the Toftestallen in Norway (1985) and Vizhijam in India (1990) [10], [11].

Great progress was made in Europe with the 1991 European Commission JOULE program that enabled the construction of two onshore pilot OWC plants. These were the LIMPET (2000), located on the Isle of Islay, Scotland, and the Pico Plant (1999), located in the Azores, Portugal. The Wavegen deployment (LIMPET) became the first grid connected WEC in the UK in 2001 and along with the Pico Plant survived as great facilities for research and development [12]-[14].

B. OWC Arrays

As with other forms of renewable energy, when power density is a function of the capture area or width of the wave, this capture area needs to be maximized. Furthermore, the economy of scale is applicable with respect to increasing capture and decreasing capital cost per WEC. Additional challenges arise with array or farm deployment such as mooring, spacing and positioning configurations, due to radiation and transmission effects of many devices in relatively close proximity.

Array spacings have been studied regarding their optimal spacing, layout and configurations mainly through prominently analytical or numerical methods [15]-[18]. Experimental research into orientation and configuration has also been carried out. In a study carried out in the Queen's University, 3D coastal wave basin with cylindrical shaped OWCs were arranged in various configurations of arrays including, terminating, attenuator, diagonal/angled and V-shaped formations. The results of these experiments proved that the terminating array was superior with respect to minimal wave disturbance and highest power capture for configuration with spacing greater than the incident wavelength [19].

Reference [20] also conducted spacing experimental tests on 1:50 scale models of free standing caissons for breakwater integration. From the above mentioned analysis, it is clear that performance is highly dependent on spacing, array configuration and PTO damping.

C. Overview of Performance

The OWC has been the subject of research for many years but a very small number have reached full-scale trials never mind commercial deployment. However, this is the case with all WEC technologies. The OWC concept and devices are competitive from an efficiency performance point of view compared to other WEC categories. This can be seen from the hydrodynamic efficiency, which is generally characterized by the Capture Width Ratio (CWR), (a ratio between captured power and the re-source of the wave per unit width). Reference [21] reviews the available CWR data for devices across many WEC categories revealing the competitiveness of the OWC.

Without considering performance values, the benefits of the OWC over other WEC types are obvious and due to several attributes, namely the simplicity of the structure and device operation. With just the free surface oscillating inside the chamber, there are no submerged moving parts, which results in easier maintenance and contributes to another crucial attribute; the robustness and longevity of the overall operation and structure. This has been proven with the ~20 years operation of the Pico power plant even with poor construction techniques [12]. Additional benefits of the OWC include its versatility with respect to deployment, geometric characteristics and applications.

The areas of improvement and negative characteristics are found more with the performance of the energy conversion. The performance losses in the energy conversion are found in the first stage with the hydrodynamic efficiency - both the hydrodynamic interaction in generating airflow (pneumatic power) and the turbine process to convert this into mechanical power.

The characteristic that provides the OWC its simple operation, it also creates a big challenge, the bidirectional airflow, which results in slow oscillations in power. The conversion of bidirectional flow is possible through various methods as reviewed in Section V. However, the alternative, having unidirectional airflow is much more desirable for obvious reasons. Furthermore, the magnitude of this oscillating power is also fluctuating since the OWC is sensitive to wave frequency and has optimal performance at its resonant frequency, which is rarely experienced in an irregular sea state. More often than not, devices are not adaptable and cannot be tuned to changing wave conditions since their natural frequency is determined by the geometrical characteristics of the OWC and thus having a small bandwidth of optimal operation.

III. MULTI-OSCILLATING WATER COLUMNS

A. Classification

The M-OWC is also commonly known as the Multi-chamber OWC in literature and there are currently at least three M-OWC subcategories: the OWC array, segmented and modular M-OWC [22]. Although there are many variations within these subcategories, the fundamental differences are found in the point at which power between the multiple OWCs is combined, whether that is at the electrical, mechanical or electrical power stage. Reviews of M-OWCs in literature exist but they are fewer than general OWC based papers [22]-[25].

An array of singular OWCs does not qualify as an M-OWC if they are not part of the same structure, which makes them a single device. Hence, an OWC array as a M-OWC has multiple singular OWCs operating in isolation of one another with individual PTOs and generators but all being part of a common structure as depicted in Fig. 1 (a) [24].

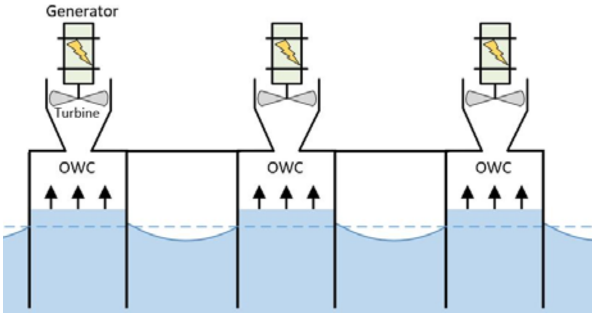


Fig. 1 (a) OWC Array as a M-OWC

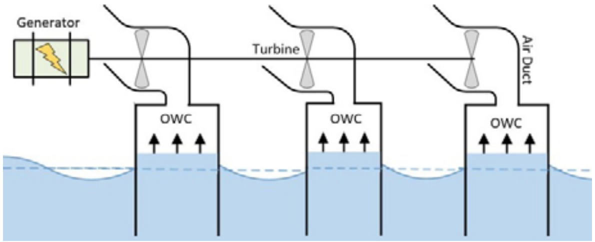


Fig. 1 (b) Segmented M-OWC Concept

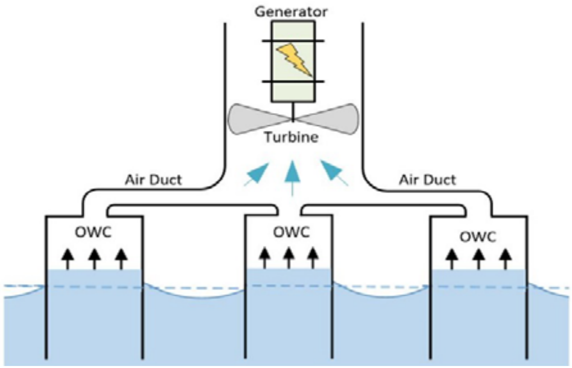


Fig. 1 (c) Modular M-OWC Concept

The segmented M-OWC (Fig. 1 (b)) is different from the array with the inclusion of the mechanical coupling of the turbine shafts to allow only a single generator. Hence, the convergence of power happens at the mechanical level rather than post generator where the power is in electrical form.

A modular M-OWC has multiple chambers contributing to airflow that converges prior to the PTO stage. Hence, pneumatic power is combined or accumulated upstream of the single PTO unit, which may contain a single, twin or multiple turbine arrangement. As depicted in Fig. 1 (c), in its simplest form, the bidirectional airflow from all chambers is fed via a manifold to the PTO. However, this may incorporate further manipulation of the airflow, especially from different orientations of modular M-OWCs as it will be discussed below.

The modular M-OWC essentially combines and consolidates the power of the individual OWCs at the pneumatic power stage, whereas the segmented M-OWC does so at the mechanical power stage and the OWC array M-OWC at the electrical power stage.

B. OWC Arrays as M-OWCs

The M-OWC concept was initiated in the early years with the Kaimei, which could be classed as an OWC Array as an M-OWC. The Kaimei, developed by the Japanese Marine Science and Technology Centre (JAMSTEC), originally had 22 OWC chambers, but was later reduced to 13 [26]. Subsequently, JAMSTEC developed the Mighty Whale (1998), which was a prototype 50 m long with 3 OWCs [27]-[29].

In more recent years, an example of an OWC array as an M-OWC is the Mutriku plant. Built in the Basque Country, Spain in 2007-2008, the plant capacity was rated at 296 kW with 16 OWCs each having their individual turbo-generators in the breakwater integrated structure (also discussed in the following sections) [30]. Before the plant was completed, storms caused severe damage to some of the OWCs, which has since been a subject for research and the plant now remains as a valuable research facility [31], [32].

C. Segmented M-OWCs

With the convergence of power occurring at the mechanical stage, the segmented M-OWC tends to be an open system, where the PTO essentially inhales and exhales from and into the atmosphere. Without individual air rectifying systems, this means that the original characteristic of the bidirectional flow still exists and therefore requires a self-rectifying turbine or a venting system.

References [33]-[35] are some of the few examples of this subcategory that exist in current research with experimental and numerical modelling of an attenuator type intended as a segmented M-OWC.

D. Modular M-OWCs

As mentioned above, the M-OWC operating system varies across the different devices found in literature. Ultimately, the main issue the modular M-OWC is trying to solve, aside from scaling up power production and efficiency, is the quality of the airflow. This means either smoothing air delivery to the PTO or rectifying the airflow to create a consistent unidirectional flow. Hence, the variations in operating systems are concerned with this manipulation of the airflow prior to the PTO. Where there is unidirectional airflow, the act of inhalation and exhalation does not occur through the entire system as with the conventional OWC – only prior to the rectifying stage.

The main variation comes with attenuator formation, where OWC chambers will respond out of phase from one another creating a need to accumulate these responses. In general, this is done using a closed system with a controlled volume of air, containing high and low pressure ducts upstream and downstream of the turbine respectively. This is normally achieved with exhale and inhale valves on each OWC as demonstrated in Fig. 2 with the SeaBreath device (previously known as the MORE) [36].

Reference [24] provides an overview of the M-OWCs with such closed systems and their respective details. These devices include the ShoreSwec (or Stellenbosch) [37], KNSWING [38], the LEANCON [39], Wave Mill [40], Waves2Watts [23], [24] and more.

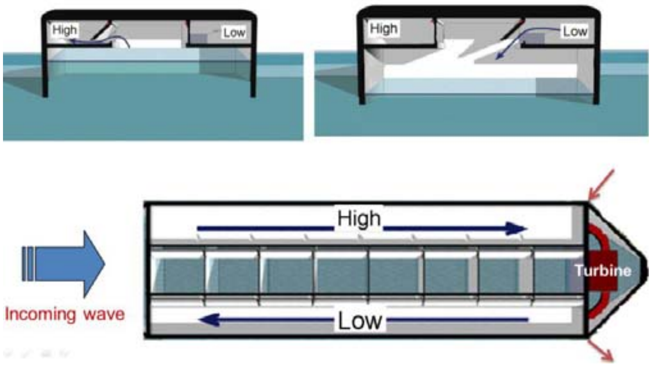


Fig. 2 The SeaBreath Concept [41]

IV. SINGULAR OWCS AND M-OWCS AS SYNERGIES

A. Potential and Costs

The renewable energy mix is market driven and therefore wave energy needs to become competitive from a costing perspective. If a device was 100% efficient but cost a colossal amount to build, deploy and maintain, wave energy would be no closer to large scale commercial deployment than it is today.

The cost of energy production is often quantified with the LCOE. This figure is dependent of three main factors: capital and operational costs, and annual energy production as depicted in Fig. 3 [42]-[44]. As with wind and tidal energy, WECs need to be deployed on a large scale. This can be done with deployment in multiples as an array of WECs to create wave energy farms, or with coupled M-OWCs – like OWC arrays as an M-OWC, segmented or modular M-OWCs. By capturing a larger area of wave energy resource, the economic benefits also scale up with reduction of the capital costs. Furthermore, from a capital cost perspective, at large scale it allows the opportunity for integration with other applications in synergetic projects, especially for M-OWCs with large platforms.

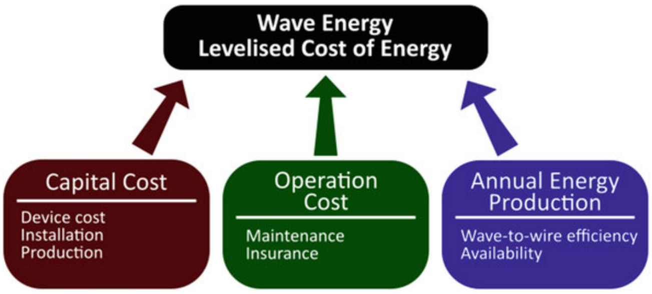
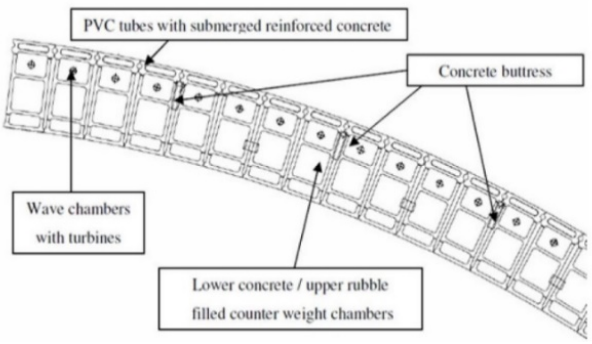


Fig. 3 Cost Breakdown of the LCOE of WECs [42]

Combinations of WECs and alternative applications are appealing because the construction costs for both purposes can be shared. For the example of the breakwater integration, there is not only the WEC generating energy but potentially a berth facility, costal protection and marina protection [20].



(a) Mutriku plant structural design [30]

(b) Mutriku breakwater completed [32]

Fig. 4 The Mutriku Wave Energy Plant Breakwater

The potential of these innovative synergies is great and a trend is developing in global research whereby focus is turning to integration of WECs with offshore platforms, structures, energy plants and more. Furthermore, as will be revealed in the following sections, larger scale M-OWCs often have a decreased number of turbines with respect to the number of chambers, especially with modular M-OWCs. It is apparent that for both an increase in overall efficiency and a reduction in PTO costs for example, the LCOE drops dramatically. The drop is more dependent on the efficiency of a PTO system; however, the combination brings vast reduction. Hence, the focus of these synergy projects should be the opportunity to lower PTO costs and improve their efficiencies at the same time [42].

B. Synergies and Integrated Breakwaters

1. Singular Onshore and Nearshore OWCs

There are a number of fixed nearshore and onshore devices deployed around the world mostly among the original OWCs mentioned above. The shore based OWCs have been built into the land, although they absorb the energy of the wave and therefore also reduce erosion, these are not exclusively known as breakwaters. The fixed on shore examples include the aforementioned LIMPET and Pico, Guangdong OWC (China), and the plant on Jeju Island (South Korea) [13], [45].

Multiple singular OWCs in terminating configurations, not necessarily as an M-OWC, but integrated into fixed shoreline defense or breakwater applications is being researched and could be the new direction for these singular OWC deployment [46], [47].

2. Nearshore and Offshore M-OWC Synergies

The number of M-OWCs deployed and undergoing research and development is and always has been comparatively lower than singular OWCs, however, recent trends are showing an increase in research for M-OWCs, or at least multiple OWCs [24].

There are examples of past deployments that are perhaps considered as synergies: the previously mentioned Vizhinjam in India and in Sakata Port, Japan [45], [48]. However, more exclusively a breakwater synergy is the Mutriku plant in north Spain (Fig. 4) [30], [32].

Through continued research, now there are many different forms of synergies, these are not only across ocean engineering fields but also across renewable energy types; for example, offshore wind energy, which requires large floating or fixed structures to support the tower. Both OWCs and other WEC types have been considered, with Fig. 5 showing the example of a turbine structure with 3 OWCs arranged at the base to provide stability and reduce costs for offshore wind turbine platforms [49], [50].

(a) twin turbine structure [49] (b) single turbine tripod [50]

Fig. 5 Wind and wave energy hybrids

Synergies or hybrids also exist solely within wave energy with an OWC and overtopping device combined to create an Oscillating and Overtopping Water Column (O-OWC). Such models as in Fig. 6 are being experimentally modelled at small scales [51], [52].

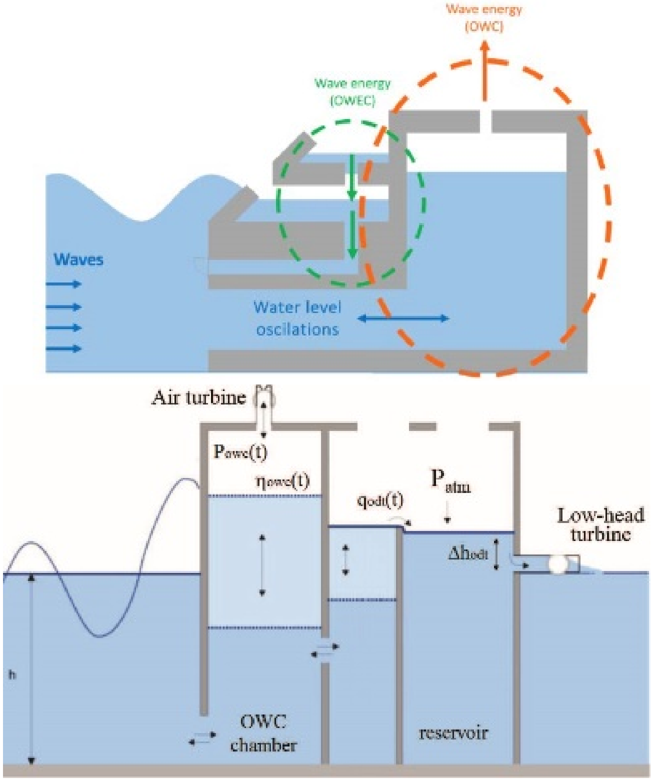


Fig. 6 Oscillating and Overtopping Water Column (O-OWC) concepts [51], [52]

With respect to offshore floating deployments, the OWC array as an M-OWC integrated into large floating platforms and breakwaters is being a common topic in reviews and case studies [53]-[61]. A great advantage of integration with large-scale synergies is the opportunity of retro fitting, not only with existing ports but also with breakwater structures around the world. One example of these concepts that is being implemented is with an array of OWCs used to obtain greater stability of a platform as with the Rho-Cee, a Pneumatically Stabilized Platform (PSP) by Float Inc., which is an Impedance-Matched OWC (IM-OWC). A large array of OWCs located on the underside of the platform improves the stability of the multipurpose platform [62].

The other major but less obvious synergy M-OWC deployment is the Sakata port plant. However, many other examples existing in literature of experimental and numerical modelling of the affects, benefits and performance analyses of the presence of OWCs in breakwater structures large or small, fixed or floating [63]-[66]. Such innovative work is the focus of many researchers around the world and forms a large part of work currently being carried out at Lancaster University [24] in the Lancaster University Renewable Energy Group, which is well known for its contributions to the field over the years [67]-[78].

V. OWC AND M-OWC PTO SYSTEMS

A. The Challenge and PTO Classification

As mentioned, the PTO system of an OWC WEC is based on pneumatic energy extraction. Extensive reviews exist in literature for OWC PTOs [13], [79], [80].

While the structure and operation of the hydrodynamic stage of the OWC is simple, it results in a complex form of power extraction in the subsequent stage of the PTO – bidirectional airflow. This is a major disadvantage with OWC operation due to constantly varying power output. Consequently, there have been many approaches to this process mostly stemming from solutions to either implement a self-rectifying turbine to operate despite the bidirectional airflow, or rectify the air to allow the use of a unidirectional turbine. A map of the categories and their subcategories is shown in Fig. 7 for a singular OWC but is also applicable for a M-OWC [81].

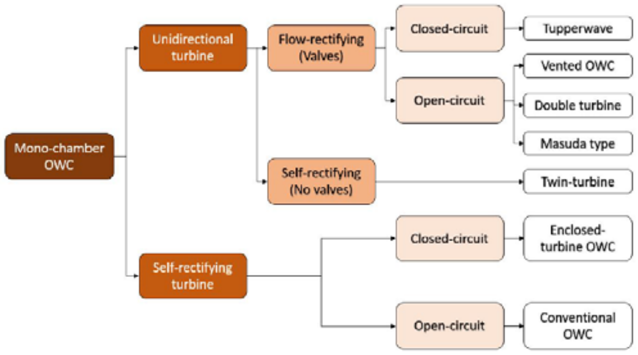


Fig. 7 Classification of approaches to PTO systems for OWCs [81]

B. Bidirectional Self-Rectifying Turbines

Power extraction from bidirectional airflow is achieved with self-rectifying turbines that rotate in the same direction irrespective of the direction of the airflow. Hence, for both the inhale and exhale processes of an OWC, although the fluid flow direction changes, the turbine is continuously rotating in the same direction. Self-rectifying turbines, their features, efficiencies and characteristics are well reviewed in literature [80]-[83] including the modelling of turbines and their variations for optimization purposes [84]-[86].

The most common of all self-rectifying turbines is the Wells turbine (Fig. 8 (a)), patented in 1976 by Dr. Wells of Queens University, Belfast [3], [87], [88]. This turbine is usually considered, the ‘default’ turbine for the OWC. Since the Wells turbine was invented, it has been the subject of much research and development in relation to its solidity, blade numbers, inclusion of guide vanes and number of guide vanes leading to many variations of the turbine across prototypes around the world: monoplane, biplane, guide vane configurations, radial inlet configurations, counter rotating rotors, variable pitch blades and more [80]-[90]. As well as being well researched over the years, the Wells turbine has featured in the deployments of the LIMPET, Pico, Osprey, Mighty Whale [27]-[29], Sakata Port [48], [91] and many other concepts under development like the Spar Buoy [13]. The Wells turbine is preferred mainly due to its simplicity and low cost, however its disadvantages are apparent with a loud operating noise, poor starting and stalling characteristics, large axial thrust, small peak operating range and operating range in general resulting in an efficiency range of ~60 – 65% [42], [92]. However, some of the more complex variations like the contra-rotating can achieve up to 75% peak efficiency [80].

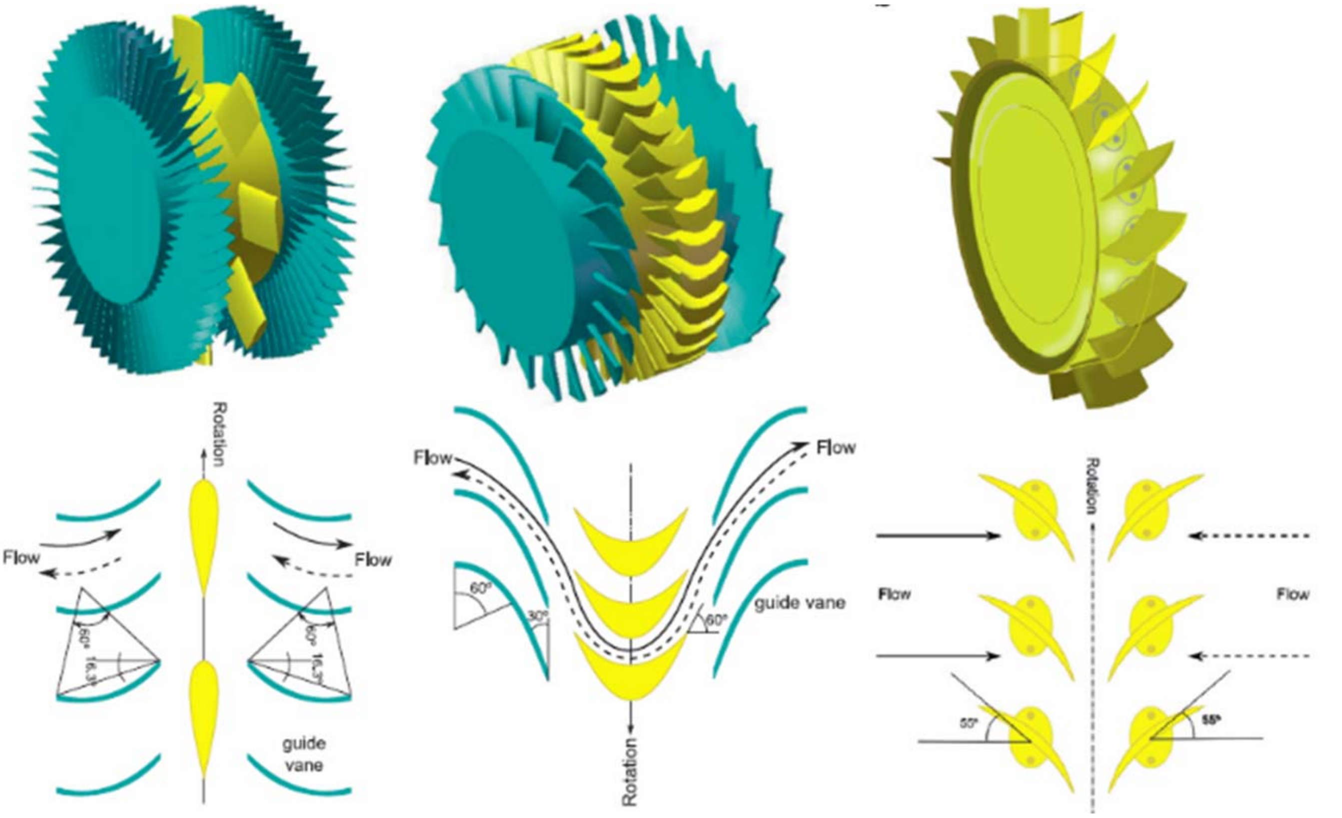
Second in popularity for OWC self-rectifying turbines is the impulse turbine (Fig. 8 (b)) – a pressure type with connecting arc shaped blades as opposed to the lift types with airfoil shaped blades (Wells turbine). Optimization points researched and available in literature include a number of aspects like the inclusion of solidity, blade geometry, guide vanes, additionally counter-rotating rotors and many more [84]-[86], [93].

It is well known that compared with the Wells turbine, in general, the impulse turbine is superior in terms of its starting characteristics, no stalling condition, lower rotational speed with a high torque coefficient, lower noise levels and a larger flow coefficient range [82], [94]. With these different performance characteristics, the self-rectifying version of the impulse turbine is often well acclaimed, but features in significantly less research. The result is fewer WEC concepts, aside from featuring in various prototypes as a retro fit for research purpose, like the FP7 CORES Project sea trial in Galway Bay, Ireland [95], [96], the Kaimei [89] and the 1991 Indian wave energy plant [97]. Its main disadvantages are its more complex geometrical design and lower peak efficiency [89].

In more recent developments, an innovative bi-radial self-rectifying turbine has emerged from the H2020 OPERA project, designed by the Instituto Superior Tecnico of Lisbon, Portugal. The turbine has undergone various stages of development, most significantly with a 30 kW prototype manufactured by Kymaner, installed and tested in sea trials with the spar buoy type OWC MARMOK-A-5 for which impressive average efficiency values were recorded albeit with a simplified control method (56%) [98].

A turbine named the Denniss-Auld turbine is a unique design with a variable pitch control (Fig. 8 (c)). The turbine was developed by Energetech, which became Oceanlinx (in Australia), to equip the three OWC prototypes of varying characteristics that the company deployed and operated before sinking into liquidation following deployment failures [2], [89], [99], [100]. The turbine has a self-adjusting pitch mechanism, much like the Wells variation but with faster adjustment based on the chamber pressures and a larger angle adjustment range. Hence it has no need for guide vanes, but employs symmetrical airfoil shaped blades with respect to the chord length as the leading and trailing edges are continuously switching rolls (Fig. 8 (c)). The turbine achieved a high peak efficiency of 63% without a drop below 35% within the operating range after the peak [80], [101].

One of the less common options of self-rectifying turbines is the Savonious. More commonly known for its use in other applications like wind energy and even as a stand-alone WEC concept [102], the Savonius has a number of long and thin arced blades and can even be mounted on a horizontal or vertical axis. Experimental work had been carried out with the Savionus turbine and in particular in a segmented M-OWC where low efficiencies were recorded [103].



(a) Wells turbine (monoplane with guide vanes) (b) Impulse turbine (with guide vanes) (c) the Dennis-Auld turbine

Fig. 8 Self-rectifying turbines for OWCs [2]

C. Unidirectional Self-Rectifying

Unidirectional turbines are known to be more efficient than bidirectional self-rectifying turbines due to the lack of need to compromise with optimization. Hence, unidirectional flow is more desirable for efficient airflow energy extraction. The challenge with the unidirectional route is the ability to change the upstream airflow conditions.

The concept of unidirectional self-rectifying PTO systems is not to include valves to manipulate the airflow but to be able to extract energy from the inhale and exhale of the OWC/s separately. This can be achieved with a twin turbine set-up, where one turbine is dedicated for inhale and the other exhale. While this has not been implemented in a device deployment, variations of the concept have been modelled experimentally and numerically.

A design of the twin unidirectional self-rectifying turbine concept is shown in Fig. 9. Frequency domain modelling of this concept was done to gain wave-to-wire efficiency (~50%) [104]. The concept was also experimentally modelled and subsequently validated the 50% wave-to-wire efficiency claims over a wide range of flow coefficients [105] and even up to 60% [107] and also with comparisons of experiments in steady and unsteady flow conditions [108], [109]. Time domain numerical analysis is also carried out, on the concept with varying geometrical features for flow field optimization purposes and assessment of turbine behavior in direct and reverse modes (Fig. 10). The conclusion of this numerical analysis found that around 1/3 of flow was wasted by the inactive turbine during either an inhale or exhale process. The wasted flow acting on the inactive turbine also produces a negative torque reducing efficiency [106]. In other numerical studies, this original twin turbine system has been modeled and compared against a single impulse turbine case [110].

The waste of flow during turbine reverse mode was then investigated further with numerical analysis and wind tunnel tests on different fluidic diodes proposed for the concept to improve the rectifying effect by reducing flow from the turbine in reverse mode (Fig. 11). Although these adaptations are said to potentially improve performance, further work is required to minimize the effects of the diodes presence with respect to the pressure drop induced in direct/forward mode [111], [112].

A further variation exists in literature with numerical analysis of the concept without fluidic diodes but with two self-rectifying turbines as the twin set-up; one Wells turbine as the main turbine and an impulse turbine to act as a booster turbine. The turbines are coupled with the intention that the Wells turbine would extract with lower flow rates and the impulse turbine with higher flow rates. This research demonstrated an improved starting efficiency of the Wells turbine with the inclusion of the booster turbine [113].

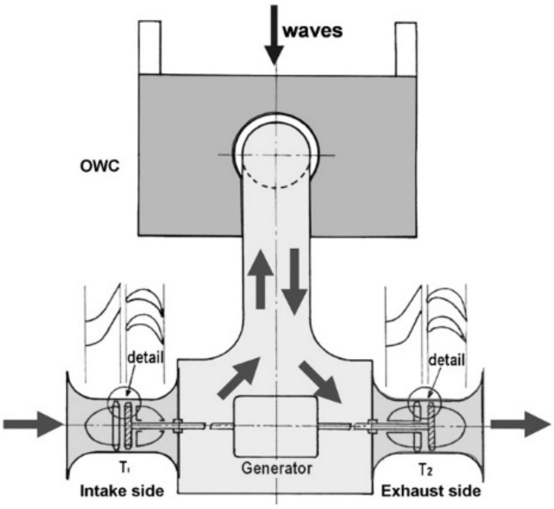


Fig. 9 Twin turbine concept designed [104] and experimentally modelled [105]

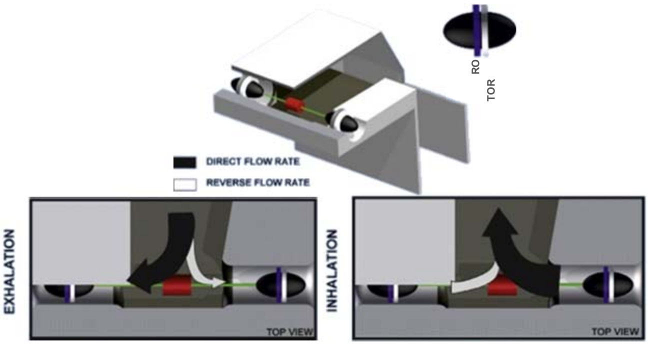


Fig. 10 Twin turbine concept subject to numerical analysis [106]

In more recent years the twin turbine concept has had a little more attention with the analyses of two unidirectional radial turbine configurations – an inflow and outflow type. However, these were not only tested as a twin set-up but also in a vented OWC case (discussed in Section V) with only one of the above configurations, meaning the counter process is vented to/from the atmosphere [114].

D. Unidirectional – Flow Rectifying

1. Closed Circuit

Flow rectifying becomes a lot simpler with an M-OWC due to the increased number of OWCs contributing to the airflow, which is a great advantage. In almost all cases, modular M-OWCs are closed systems/circuits. This includes the aforementioned SeaBreath (Fig. 2) [36], [41], [115], ShoreSwec [37], [116]-[119], KNSWING [38], [120]-[122], and the LANCON [39], [123]-[125]. With all these systems, each OWC in the M-OWC device inhales and exhales through one-way valves into the high-pressure and low-pressure ducts respectively. Due to the orientation of these devices with respect to the wave direction, all OWCs are out of phase and therefore inhaling and exhaling at different instances theoretically resulting in smoother and constant airflow caused by the pressure drop between the high and low pressure ducts/manifolds.

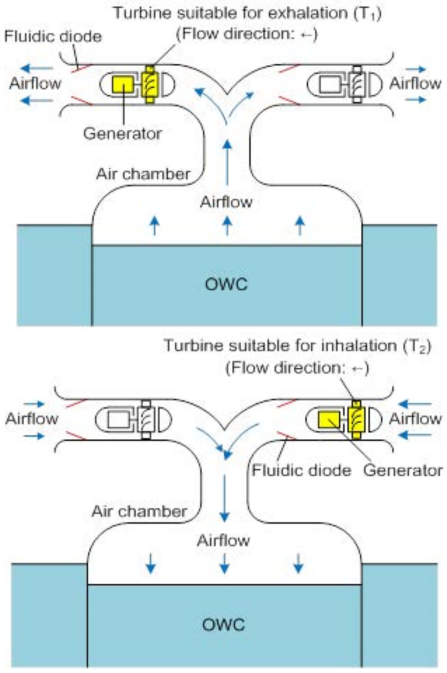


Fig. 11 Concept modeled numerically [106] and later with inclusion of fluidic diodes [111]

Singular OWC closed circuit concepts are rarer due to the losses induced by the valves. However, these concepts do exist [126] and have been the subject of research like the additional chambers mounted above the OWC for high-pressure and low-pressure air from the OWC exhale and inhale process respectively. In between these chambers is the unidirectional turbine [127]. Although the performance results of the Tupperwave were competitive against a comparative Spar Buoy model, the majority of the losses were due to the one-way valves and their opening time and the excess damping caused as a result [128].

2. Open Circuit

An open circuit/system is the one that inhales and exhales from the atmosphere and hence the pressure drop across the turbine is always relative to the atmospheric pressure.

A vented OWC is an open circuit that creates unidirectional airflow by only using half the wave period and vents the atmosphere during the other half of the period.

As well as the studies discussed in Section V [114], an example of this is the UniWave concept under development by Wave Swell Energy Ltd. Australia [129]. During inhalation only, when the water column descends, air is drawn from the atmosphere and through a unidirectional turbine. As the OWC is heaving, pressurized air is exhausted to the atmosphere via a valve, which resets the chamber pressure to atmospheric at the maximum internal heave level [129]. This rationality likely based off such research that proves that the exhalation process is less efficient that the inhalation [130].

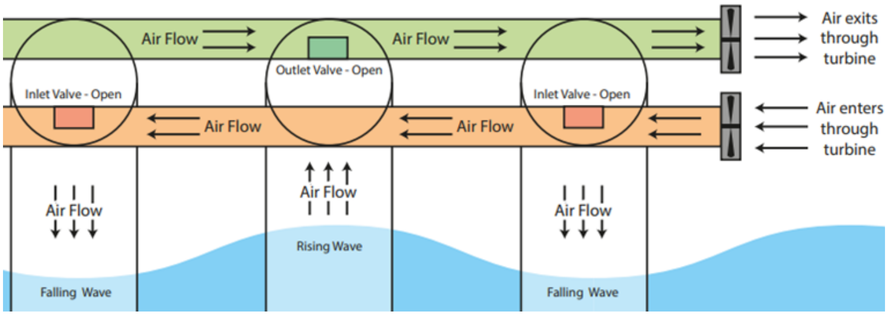
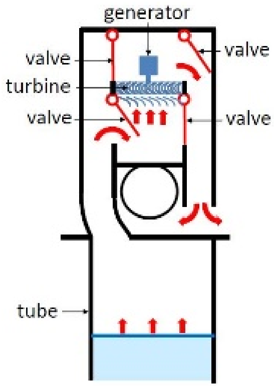
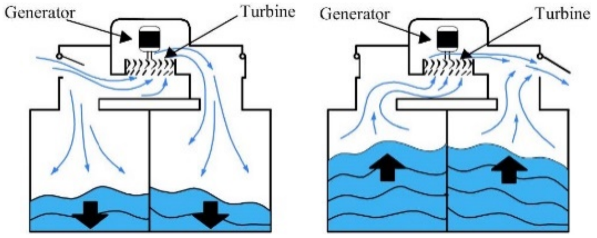


Fig. 12 Wave Mill PTO system schematic [40]



(a) single OWC [13]



(b) M-OWC rectifying PTO system [84]

Fig. 13 Masuda type rectifying PTO systems

An open circuit double or twin turbine concept for an M-OWC is best demonstrated with the WaveMill, an Australian invention patented in 2009 [131]. Originally developed by iVec and named the Floating Wave Power Plant (FWP) [132] it is now under a new name with Wave Power Engineering Ltd. [40]. Essentially cousins of the twin unidirectional self-rectifying concepts discussed above, with the addition of valves and ducts to separate high and low pressures, the turbines are only connected to their respective ducts for the inhale and exhale processes (Fig. 12). Hence, similar to the other M-OWCs with closed circuits, each OWC has two one-way valves for inhale and exhale.

For singular OWCs or M-OWCs without valves as part of the OWC chamber there are further rectifying methods, starting with the original Masuda invention of the navigation buoy (Fig. 13) [13]. The airflow duct from the OWC chamber is connected to a rectifying unit with a unidirectional Francis turbine and four one-way valves [84]. A two-valve dual chamber version of the rectifying system was later tested in the Kaimei device at sea trials (Fig. 13), which confirmed doubts of viability. At this larger scale, the valves proved to over complicate manufacturing, maintenance and operation resulting in poorer performance [9], [13], [84].

Valves were rarely considered, due to their impracticality and potential reliability issues at larger scales. The combination of larger flowrates and the required quick response time means that they are unfavorable [13]. Such rectifying valves were first implemented in the PTO system of the original navigation buoys mentioned earlier (Fig. 8 (a)) and the Kaimei (Fig. 8 (b)), where the unreliability of the valves were confirmed with sticking and generating losses.

VI. CONCLUSIONS REMARKS

This paper has provided a review for OWC WEC technology in the light of its recent advancements and the authors' predictions of its potential development areas in the near future. The review has covered the two main aspects of the OWC development that is considered the most crucial in research today in order to improve wave energy competitiveness by ultimately lowering the LCOE through upscaling deployment, diversification through innovative synergies, and performance enhancement through PTO system improvements. The two areas refer to the lowering of capital costs, and potentially improvement of annual production through greater efficiency of large-scale deployments and M-OWCs.

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