# Chapter 4
# Development of Oscillating Water Column and Wave Overtopping—Wave Energy Converters in Europe Over the Years

**Krisna Adi Pawitan**

**Abstract** The latest Intergovernmental Panel on Climate Change (IPCC) in 2018 gave the clearest yet call for immediate action to reduce the amount of human-related activity $CO_2$ emission. This fueled researchers to explore more sustainable ways of harvesting energy over the years, with ocean waves being one of the most attractive sources of renewable energy. This chapter will initially explore multiple ways of devices to harvest the energy from an ocean wave. The exploration then focuses on the development of Oscillating Water Column (OWC) type Wave Energy Converter (WEC), especially after the introduction of perforated vertical breakwater back in 1961 which open the possibility to combine both energy generation capability and coastal protection in the same structure. Examples of several projects which have been done in the past and are currently under construction in Europe will be given as an illustration of the current progression in the utilization of wave energy using OWC technology. Also, a Wave Overtopping Device—Wave Energy Converter will also be explored in a similar manner. A couple of representative project examples will also be given to similarly illustrate current progress on the development of such devices until now.

## 4.1 The Importance of Wave Energy Resources Utilisation

The intergovernmental Panel on Climate Change (IPCC) 5th assessment report (AR5) [1] indicates a clear involvement of human activities in the increase of average global temperature. It also stated that global warming leads to an increase in sea level. According to the AR5 IPPC report in 2014, the increase in global temperature is extremely likely to have been caused by anthropogenic gasses which increase the concentration of $CO_2$ in the atmosphere. The latest IPCC [2] report further indicates an increase in temperature in excess of 1.5 °C above the pre-industrial level. This

K. A. Pawitan (✉)
Quantum Wave Microscopy Unit, Okinawa Institute of Science and Technology Graduate University, Okinawa, Japan
e-mail: krisna.pawitan@oist.jp

is the clearest yet call for immediate action to reduce the amount of $CO_2$ emission. To reduce the amount of greenhouse gasses in the UK, Department of Energy and Climate Change releases the Carbon Reduction Commitment (CRC) which pursues the target of cutting the $CO_2$ emission by 60% from 1990 levels by 2050 in the region. This plan pushed the development of greener energy generation ahead of "dirtier" energy sources, such as coal and natural gas. It is estimated that for every 1 kWh produced by marine renewables, the $CO_2$ emission can be reduced by 394 g when compared to Combined Cycle Gas Turbine (CCGT), 120 g when compared to Biomass, 937 g when compared to Coal powered energy generator, and about 1000 g when compared to Diesel power with 25% efficiency [3]. Fueled by the initiative, Scotland's renewable energy generation for consumer electricity in the last 10 years tripled the production to about 10GW by 2018 or accounted for over 70% of the total electricity used in Scotland. Wind energy, which accounted for about 71% of the total renewable energy generation, remains the biggest contributor by 2019. The wave and tidal energy sector, on the other hand, only responsible for about 0.18% [4]. This gives room for improvement for the wave energy sector to be developed and to have a bigger contribution to the world's total energy generation.

Among many renewable resources, the ocean remains as the biggest energy resource waiting to be harvested. It is calculated to be as much as 1000 GWh of wave energy reaching the British Isles every day on average [5]. The world energy council approximated no less than 29,500 TWh/yr of wave energy available, with the densest energy potential located in Europe and the west coast of America [6–8]. This source of energy, contrary to the theoretical energy potential suggested, remains underused compared to other renewable energy resources such as wind and solar [9, 10], with conversion technologies at a relatively early stage of development and with consequent high energy cost. In order to harvest, one needs to understand how a sea-wave forms. To put it simply, (wind-induced) wave is basically energy passing through the surface of the water. This energy mainly comes from the wind and is then transmitted across the ocean through the water. A stronger wind, which often occurs in the middle of the ocean, blows the surface of the ocean water and creates waves. The wave travels toward the coastline transmitting the energy to an accessible location. This form of energy, along with offshore wind and sea tidal and current, is commonly known as marine renewables. Deployment of wave energy converter technologies, unfortunately, is lagging behind the other two, due to its high cost of about EUR 330–630/MWh, which quite far compared to the target set by the European Union of USD 220/MWh by 2025 (IRENA [8]). This is worsen by poor performance of several pilot projects to date. This, at the same time provides a wide opportunity for a creative mind to fill in the gap in wave energy utilization and figure out the best way to harvest the energy. The following subchapter will explore the development of the wave energy utilisation attempt that has been done over the years, including a more in-depth overview of the development on the Oscillating Water Column (OWC) research with several examples of such projects, particularly in Europe, given as a representation of the general development of the device. Furthermore, a brief introduction of wave overtopping devices will be given

similarly, including several examples of the projects which had been done in the past and are currently running, particularly in Europe.

## 4.2  A Brief Introduction to Wave Energy Harvesting Mechanism

Even though wave energy has been established as one of the biggest potential sustainable energy resources over the last 70 years, the mechanism for which the energy is taken from the ocean has not been converged. Many types of WECs have been developed in the past to harvest some of this ocean energy while surviving the harsh operation condition on-site at the same time. There are many types of wave energy converter developed to date, among them, there are four types of mechanism that stand out called wave attenuator, point absorber, wave overtopping, and Oscillating Water Column (OWC)—Wave Energy Converters (WEC). A wave attenuator is a floating Wave Energy Converter (WEC) of which the energy is generated by means of relative motion between two arms of the device. Because the device is floating, it can be rotated to face the direction of the incoming wave to guarantee maximum wave absorption in accordance with the design characteristics. Point absorber is also a floating WEC that took advantage of floating buoy(s) which oscillate up and down as the wave passes and connected to an energy extraction mechanism from such motion. In general, this type of WEC can absorb wave energy from multiple wave directions. On the down side, these types of WECs need to be positioned in a difficult-to-reach location and require additional effort for maintenance, such as towing to near-shore position, furthermore because these devices only serve as energy generation, the cost then wholly intended for energy generation. Wave Overtopping and Oscillating Water Column (OWC) devices, on the other hand, have advantages due to their simplicity in energy harvesting mechanism (often leads to low maintenance cost) and their ability to be combined with coastal protection building, such as breakwater or seawall, thus allows the cost to be split between energy generation and coastal protection. Without discounting the importance of other types of WECs mechanism, the following sub-chapters will be focused only on the development of Oscillating Water Column (OWC) and Wave overtopping types of Wave Energy Converter, especially in Europe.

## 4.3 Oscillating Water Column (OWC) Type Wave Energy Converter

### *4.3.1 General Introduction of OWC*

The general principle of an OWC can be seen in Fig. 4.1. In general, an OWC device utilises wave crests and troughs to drive the water column trapped inside the OWC chamber to oscillate up and down. This oscillation occurs due to hydrodynamic pressure variation at the column base. These water movements, furthermore, force the air inside the chamber to move out and in via an air channel. The power generation can then be done by placing a power take-off mechanism in this air channel.

The development of an Oscillating Water Column started in the 1940s with the development of a floating OWC device to power a navigation buoy [11–13]. It was designed and developed due to its simplicity and potential for having relatively low maintenance and therefore the initial development was only focused on energy generation. Only after the idea of a perforated vertical breakwater was established in 1961 by Jarlan [14] that showed the advantage of having a wave absorption chamber to reduce the wave loading experienced by the front vertical wall breakwater, engineers then began to study the possibility of combining OWC concept into a vertical breakwater [15] thus making the possibility of higher survivability in the coastal defense structure while producing energy at the same time. These studies found that integrating an OWC into a vertical breakwater is not only possible but also has the theoretical potential of 100% energy absorption [16]. Apart from the energy absorption capability, by definition, a coastal protection structure should be exposed to a highly energetic portion of the ocean. This, in turn, will enable the WEC device to be exposed to those energetic portions of the ocean as well. This scheme, furthermore, enables the ability to share the cost between the energy generation and coastal protection constructions.

**Fig. 4.1** Simplified version of an Oscillating Water Column schematics
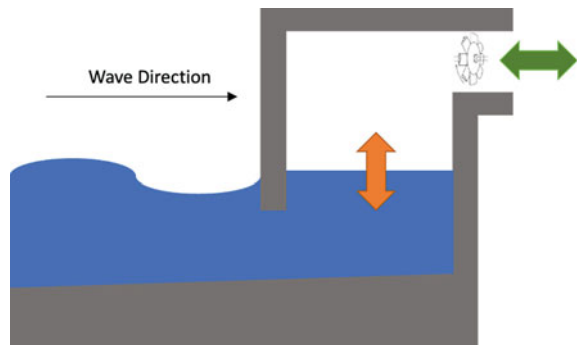
## 4.3.2  Working Principle and Design Analysis of OWC

Due to the working principle of the device, minimum submerged moving parts are needed for the device to generate power, thus the possibility of mechanical failure due to salt-water and metal interaction is estimated to be minimal. Although it is important to be noted that the air flowing out of and into the chamber may be very humid and saturated with salt-water spray. Over the years, many researchers have explored the optimum design of an OWC. In general, the studies focused on the front wall wave loads, OWC caisson dimensioning, and on power take-off optimisation. Small-scale physical model studies found that an inclined-slope front wall will reduce the wave loads experienced by the front wall but will have a higher wave transmission coefficient when compared to an ordinary vertical wall [15, 17]. Subsequent studies also found that the front wall geometry and the front penetration—defined as the depth of the submerged part of the front wall divided by the distance between the still water level (*swl*) and the OWC's chamber floor—also play a significant role in determining the overall efficiency of the device, with typical efficiencies of up to 70% reached. Furthermore, [18, 19] hypothesized that the total forces acting on the front wall will be the sum of wave pressure distribution and hydrostatic pressure distribution and are reduced by the opposing pressure distribution acting on the in-chamber side of the front wall. Unfortunately, hitherto, there have been no experimental or numerical results to support this argument. In addition to the wave loading, [15] published guidance to select the dimension of the OWC caisson design based on the wave characteristics. For an OWC design, there are three most influential geometries: chamber width ($B_c$), submerged front wall ($w$), and chambers height (crest freeboard) ($h_c$) (Fig. 4.2). Takahashi [15] also recommends several values for the OWC installed breakwater design based on the hydrodynamic efficiency and structural stability as follows: $B_c$ equal to about 0.13L (wavelength), $w$ equal to about $0.25H_{max}$ (highest incident wave height), and $h_c$ equal to about $1.0H_{m0}$. Here $H_{max}$ refers to the highest

**Fig. 4.2**  Most influential geometries in designing an OWC chamber after Takahashi [15]: chamber width ($B_c$), submerged front wall ($w$), and chamber height ($h_c$)
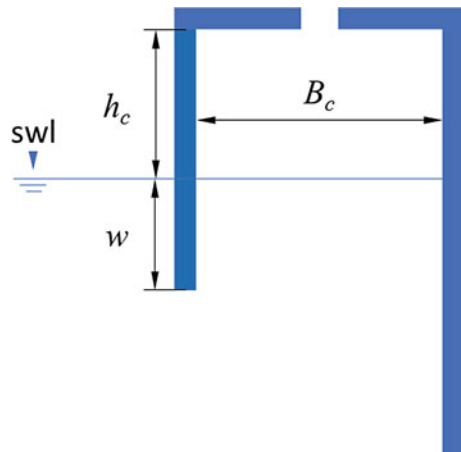
individual wave height in a record, while $H_{m0}$ or the significant wave height is defined as an imaginary higher one-third wave and calculated as the mean of the top 1/3 wave height in descending order in a given record.

After the dimensions related to the OWC chambers have been selected, it is important to continue the exploration into the loads acting on the in-chamber walls. For the front wall facing seaward, a lot can be borrowed from the coastal engineering research on the wave loadings on a vertical wall breakwater. One of the most prominent and commonly used predictions in that field is the trapezoidal pressure distribution with the maximum pressure occurred on the still water level proposed by Goda [20, 21]. The prediction tools themselves enables the engineers to calculate the pressure at the still water level (refer to as $p_1$), the pressure at the bottom of the breakwater foundation ($p_2$), at the toe of the breakwater ($p_3$), and finally the uplift force experienced by the breakwater due to wave loadings ($p_4$). The trapezoidal shape mentioned and the location of $p_1$-$p_4$ summary are illustrated in Fig. 4.3. Here η indicates the height to which the wave pressure is exerted, and $d$ denotes the distance between the still water level and the toe of the breakwater.

Because the wave loads experienced by the front wall are assumed to be similar to a conventional breakwater, now in-chamber wall's wave load is important to be discussed. Early exploration on the rear wall wave pressure was done leading to the then proposed 4 MW wave generator at Siadar Bay, Scotland. For the sake of preliminary design, [22] then postulates that the wave pressure distribution acting on the rear wall of the air chamber may come from the "missing" part of the front wall and the pressure distribution should be hydrostatic as illustrated in Fig. 4.4 by red arrows.

However, more recent small-scale physical model results, using a regular wave experiment, suggested that the pressure acting on the rear wall is closer to a Goda-like pressure distribution [23]. Building upon large-scale experimental results, [24] expanded the in-chamber wave loading prediction to include both the chamber's rear
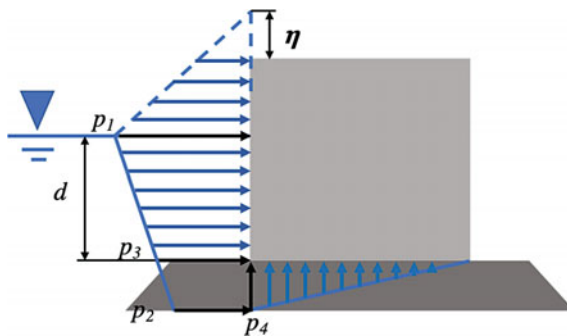


**Fig. 4.3** Simplified illustration of the trapezoidal wave loading proposed by Goda [21]. Here $p_1$ denotes the pressure acting at still water level, $p_2$ at the bottom of the breakwater foundation, $p_3$ at the toe of the breakwater, and $p_4$ the uplift pressure due to incident wave. η indicates the height at which the wave pressure is exerted to
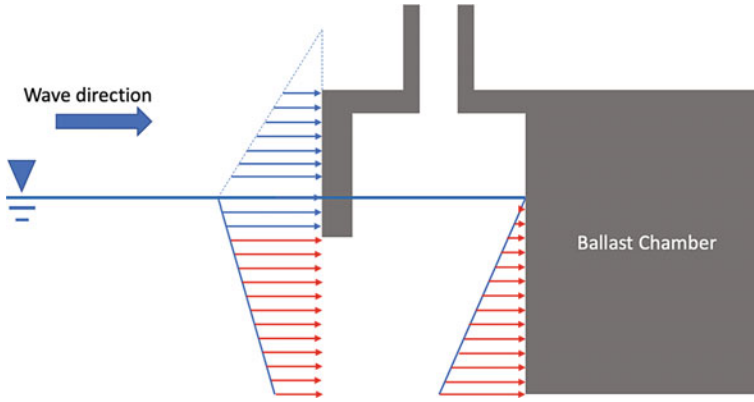
**Fig. 4.4** Illustration of hypothesised pressure distribution on the rear wall after Patterson et al. [22]

wall and the chamber's ceiling by modifying the incoming Goda-like trapezoidal pressure from the incident wave. The expanded method incorporates a transfer coefficient ($K_t$) to the integrated pressure calculation introduced by Goda [20], hereafter referred to as $F_{GODA}$. The transfer coefficient ($K_t$) itself is based upon the front wall submersion relative to the water depth at the toe of the device and can be calculated as follows.

$$0 \leq \frac{w}{d} \leq 0.3 \rightarrow K_t = 1$$
$$0.3 < \frac{w}{d} \leq 0.9 \rightarrow K_t = \frac{0.81 - 0.7(w/d)}{0.6}$$

The "transferred" in-chamber integrated pressure ($F_t$) then can be calculated as follows,

$$F_t = F_{GODA}.K_t$$

The authors suggested that the rear wall pressure changes depending on the chamber's condition and separate the estimation method into closed chamber condition indicating zero air escape thus zero energy production, fully open chamber condition indicating zero chamber pressure buildup thus zero energy production, and operating chamber condition, which is defined as the intermediate condition between the first two extremes mentioned, demonstrating that the pressure acting on the in-chamber rear wall probably closer to the one illustrated in Fig. 4.3 instead of the one shown in Fig. 4.4. A very simplified concept of this can be seen in Fig. 4.5. To indicate the transition state of the operating condition, the authors also introduce *proportion coefficient* ($P$) which indicates the condition of the chamber with $P = 1$ meaningfully closed and $P = 0$ meaningfully open. The author proposed the following empirical formula to calculate the *proportion coefficient* ($P$),
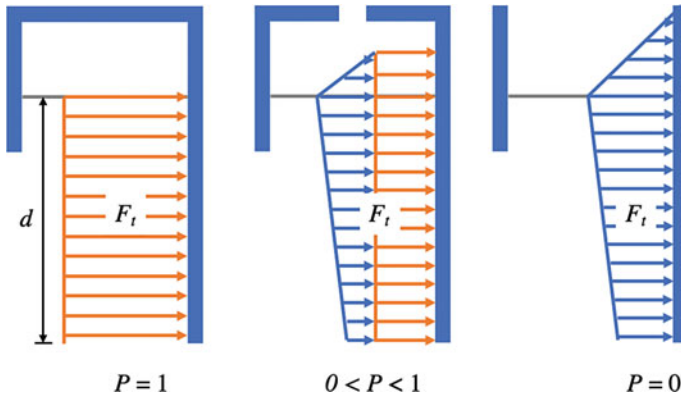
**Fig. 4.5** The pressure distribution schematics for the operating condition at various openings are represented by $P$ values. The opening illustration is exaggerated in this figure, subfigure **a** closed chamber condition ($P = 1$), **b** intermediate cases, and **c** open chamber condition ($P = 0$)

$$P = f\left(\frac{A_o}{A_c}\right) = 1 - 45.55\left(\frac{A_o}{A_c}\right)$$

Here the $A_o$ and $A_c$ represent the ratio between the opening orifice area ratio and the chamber area ratio respectively. It is important to note here that the author draws a comparison between the air restriction caused by the turbine's rotation into the opening: chamber area ratio and both fully closed and full open conditions is situations where the wave energy generator is not functioning. This prediction method, furthermore, ignores the sea-ward pressure that occurs on the rear part of the front wall because that will reduce the total landward horizontal force experience by the whole structure thus making the prediction conservative.

After determining the case of interest, then the pressure distribution on the in-chamber rear can be calculated using the following formula for fully closed ($(F_t)_{closed}$)

$$(F_t)_{closed} = K_t.F_{Goda} = p_c d$$

where $p_c$ denotes the chamber pressure and $d$ denotes the distance between the still water level and the OWC chamber's floor. For fully open condition the following formula can be implemented to predict the wave pressure acting at the still water level ($p_{tswl}$) and at the OWC chamber's floor elevation ($p_{tbot}$)

$$H_t = H_{max}\, K_t$$

$$\alpha_{swl} = \left[0.6 + 0.5\left(\frac{4\pi h/L}{\sinh(4\pi h/L)}\right)^2\right] + \left[\min\left\{\frac{h_b - d}{3h_b}\left(\frac{H_{tr}}{d}\right)^2, \frac{2d}{H_{tr}}\right\}\right]$$

$$\alpha_{bot} = 1 - \frac{d}{h}\left[1 - \frac{1}{\cosh(2\pi h/L)}\right]$$

$$p_{tswl} = \alpha_{swl} \, \rho \, g \, H_t$$

$$p_{tbot} = \alpha_{bot} \, p_{tswl}$$

$$\eta_t = 1.5 \, H_t$$

where $H_{max}$ stands for the maximum wave height ($H$) measured in a series of the wave train, $L$ denotes the deep-water wavelength, $h$ denotes the water depth in front of the structure, and $h_b$ denotes the water depth at the location of $5H$ in front of the structure. So that the integrated pressure $(F_t)_{open}$ can be predicted using

$$(F_t)_{open} = 0.5((\eta_t + d)p_{tswl} + dp_{tbot})$$

For the operating condition, the integrated pressure $((F_t)_{operate})$ can be estimated using the proportion coefficient mentioned earlier and using the following formula

$$(F_t)_{operate} = P(F_t)_{closed} + (1 - P)(F_t)_{open}$$

$$(F_t)_{operate} = P(p_c(d + \eta_{tr})) + 0.5(1 - P)((\eta_t + d)p_{tswl} + dp_{tbot})$$

where the $\eta_{tr}$ should follow

$$\eta_{tr} = \begin{cases} 0, & if \ P = 1 \\ \min(1.5 \, H_t \, , \, h_{ceil}), & if \ 0 \le P < 1 \end{cases}$$

With $h_{ceil}$ indicates the distance between the OWC chamber's ceiling and the still water level. Recent findings also suggested that introducing an OWC caisson may lead to a reduction in wave reflection of a vertical breakwater [25].

The aforementioned front wall load (e.g. [18, 23]) and the in-chamber wall load studies (e.g. [23, 24]) are mostly focused on the non-impulsive wave loads, but one of the biggest concerns in a conventional vertical breakwater design is in impact loads. Unlike non-impulsive wave loads, impulsive wave loads (commonly as a result of wave breaking in front of or at the location of the breakwater) can results in a much higher peak local pressure (e.g. [26, 27]). Several examples were shown before where ignoring such pressure during design processes may lead to dire consequences for breakwaters by Oumeraci [28]. Since the water column of an OWC is "protected" behind the front wall and ideally is not exposed to the ocean surface, the water column inside the chamber is mostly assumed to be well-behaved during design stages, including when determining the device performances. Subsequent research [29], on the other hand, observed that an impact phenomenon might also occur inside the chamber. A Particle Image Velocimetry (PIV) exploration also suggested that such impact may occur due to a vortex that developed behind the front wall opening when the water column is moving upward [30]. Apart from the structural influence, non-ideal water column conditions can be expected to have a negative effect on the wave energy conversion efficiency of the device. One could imagine that the chaotic water column movement may increase the amount of larger-scale turbulent motions in the

chamber, which could lead to a significant reduction in energy extraction capability. Additionally, due to the fact that if the moisture in the air chamber exceeds 65%, the power extraction capability may decrease by about 50–70% [31]. Focusing on the impact force acting on the structure, [32] shows the wave condition at risk at various power take-off setting conditions. The author further argues that an impact that occurs at the front of the wall may lead to an impact occurs inside the OWC chamber, with the highest impact pressure recorded on the ceiling of the chamber instead of the internal rear wall. This location increases the possibility of sliding and overturning of the entire coastal structure, thus increases the importance of impulsive wave loads consideration to be included during the design process.

## 4.4 Oscillating Water Column Type WEC Projects Developments History

Over the years, there have been several OWC pilot projects developed around the world, especially in Europe. Among many early examples, there were two shoreline OWC projects that stand out due to their early full-scale prototype testing called Land Installed Marine Power Energy Transmitter (LIMPET) in the Isle of Islay, UK, and Pico power plant in The Azores, Portugal. Soon after that, the world's first grid-connected OWC installed breakwater was constructed at the port of Mutriku, Baque Country, Spain between 2009–2012, and the U-OWC type WEC in the Port of Civitavecchia in Italy followed in 2011 [33], which mark the beginning of the integration between coastal protection structure with energy generating device which, hopefully, will become more mainstream in the future. This section will discuss the development of OWC, especially in Europe, through the aforementioned OWC devices. In addition to the bottom-stand OWC projects, several examples of early floating OWCs development around the world will be discussed briefly.

### 4.4.1 Land Installed Marine Power Energy Transmitter (LIMPET)

Named after a small marine mollusk, the Land Installed Marine Power Energy Transmitter or LIMPET was designed and developed by the Queen's University of Belfast and constructed on the Isle of Islay, Scotland. When it started its operation in 2001, LIMPET was the first grid connected WEC in the world. The wave energy converter is an onshore oscillating water column and was designed to generate 500 kW of electricity. Figure 4.6 shows the schematic of LIMPET power plant which comprises of three 6 m by 6 m concrete chambers with 40° inclined front wall.
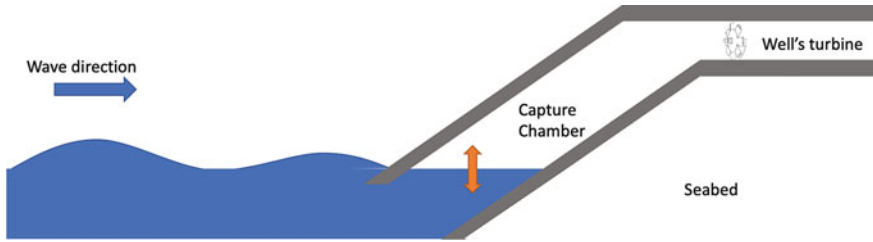
**Fig. 4.6** Simplified schematics of LIMPET power plant in the Isle of Islay after [34]

The front wall inclination was selected after a small-scale test of 1:36 scale model experiments found that compared to a vertical structure, the 32.7° front wall inclination led to a 36% wave pressure reduction, and the −32.7° angle (inner chamber part of the front wall) reduced the wave loads experienced by the inner chamber by as much as 56% [17]. However, the experiment only used a single regular wave period of 1.49 s and the same small-scale test later showed large vortices appeared at the "lip" of the front wall during the water inflow and outflow and a breaking wave hitting the chamber's rear wall in a high incident wave cases [29] indicating possible high-efficiency losses during such cases.

A LIMPET performance report published after the conclusion of the project indicates breaking wave loads of up to 690 kN/m$^2$ experienced by the prototype which consistent with the small-scale test [34]. These results may show some of the reasons behind LIMPET's poor performance during operation, with only generating up to 100 kW of its peak, about 20% of the rated capacity. Anecdotal evidence points also to a lot of wave energy being dissipated by wave breaking in the shallower part of the water seaward of the plant, including the loud noise made by the turbine during operation. Despite these performance issues, the project demonstrated that the OWC wave energy converter's simplicity can offer excellent reliability by performing 98% of its lifetime [35]. This is shown by the past experienced that the plant didn't require a lot of routine maintenance check-ups and was quite robust against any weather condition. It is also important to remember that the power plant was located on the shoreline instead of the nearshore.

### 4.4.2 Pico Power Plant

In parallel with LIMPET design and production, another full-size fixed-structure OWC was initiated on the island of Pico, Azores, Portugal. The power plant was built under the coordination of Instituto Superior Tecnico (IST). The structure consists of a single 12 m by 12 m cross-section water column in a concrete chamber, standing on the sea bottom. The device was rated at 400 kW and was completed in 1999. The highest sustained energy output recorded was about 7.5 MWh during a near 400 hours of continuous production in November 2001. The development of the

device included a wide range of scales physical model tests from 1:35th test in a wave flume to a 1:4th physical model test in actual seawater. After almost 20 years of operation, the wave power plant is finally closed due to some partial failure in the base of the wave energy converter, according to the press release by WavEc in 2018. Another site of the same island is currently under assessment for wave energy generation power plants following the decommissioning of the Pico power plant [36].

### 4.4.3 Mutriku Wave Energy Plant

Unlike coastline OWC structures such as LIMPET and Pico plants, the Mutriku wave energy plant is located in the deeper and more energetic location of the ocean where a breakwater is needed as harbor protection. The OWC type chamber is installed in an already designed approximately 440 m long breakwater as shown in Fig. 7a from above, courtesy of an open street map. Figure 7b shows the same structure taken from the ocean in front of the vertical wall, courtesy of [37]. As can be seen here, some of the front wall's outer layer "peels-off" due to extreme wave pressure during the storm. The construction was promoted by Basque utility Ente Vasco de la Energia (EVE). The main challenges faced by the WEC's designers at that time were making a WEC design that will not interfere with the harbor accessibility and will not cause many alterations to the breakwater's original design [38]. The team later decided that an OWC concept could best fulfill both requirements, with the final design of the OWC installed breakwater specified 16 OWC chambers, each connected to 18.5 kW self-rectifying Wells turbine with a rated power of 296 kW in total. The turbine used in this project is the same design as LIMPET. Unlike LIMPET, however, this project used separate power take-off (PTO) system for each chamber.
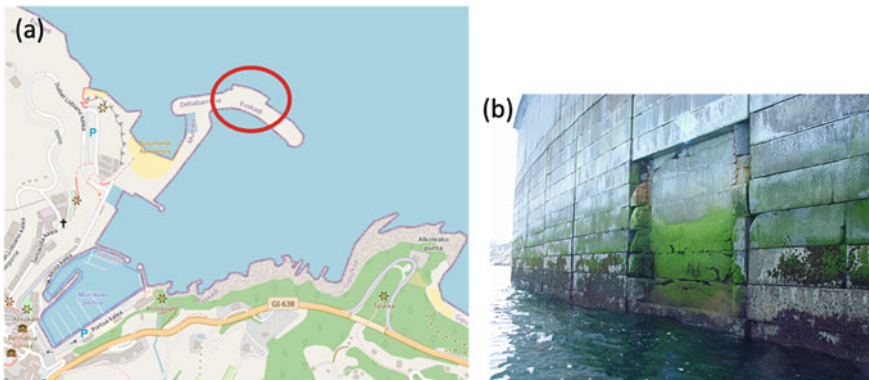


**Fig. 4.7** The OWC type chamber is installed in an already designed approximately 440 m long breakwater **a** from above, courtesy of Open Street Map and **b** the same structure taken from the ocean in front of the vertical wall, courtesy of [37] with permission

The developer claims that the power generator will avoid 600 tonnes of $CO_2$ emission annually, although it is interesting to consider the embodied $CO_2$ in raw materials and the construction process. Nevertheless, the breakwater is much-needed harbor protection for the area, so included a wave energy harvesting mechanism should bring an advantageous addition to the existing design. Another intention of the project is to make the Mutriku a reference point in marine energy development which was successfully achieved upon the commissioning of the project and marked as the world's first grid connected OWC installed vertical breakwater in the world.

Although now it is operating, the construction was not a smooth process, suffering from severe storm damage in December 2007, March 2008, and January 2009. These storms caused 4 of the 16 chambers to be partially destroyed (Fig. 7b), including the loss of the entire section of the front wall [37]. A subsequent study suggests that the pressure experienced by the structure may have reached 6 times the operational limits of the front wall during these storms [39].

### 4.4.4 Resonant Wave Energy Converter (REWEC) or U-OWC

Europe's newest wave energy power plant project based on the OWC design as per writing is the Resonant Wave Energy Converter 3 (REWEC3) or as also known as the U-OWC type WEC credited to the additional wall extending in the front of the front wall forming a "U" shaped wave duct as shown in Fig. 4.8 [40]. By adding this vertical wall, the resonance of the device can be better tuned to a larger wave condition, which should lead to a higher absorption rate under-designed wave characteristics. Subsequent research [41] further estimated that for the identical size structure, the U-OWC may absorb 90.7% of the wave energy compared to only 15.6% of the simple conventional OWC configuration, or about 5.5 times more electricity generation. The results, however, was only done for irregular sea condition with



**Fig. 4.8** The Resonance Wave Energy Converter (REWEC) or U-OWC schematics after Boccoti [40]

Wave Direction
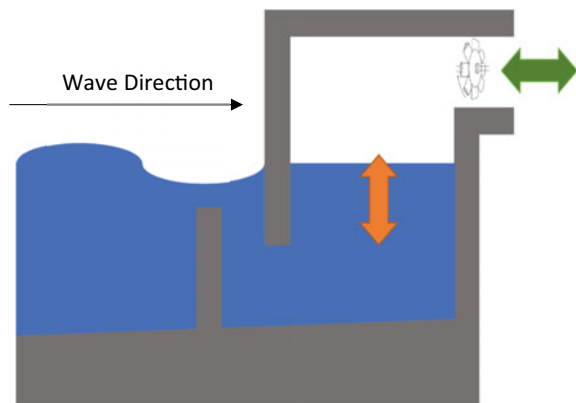
significant wave height ($H_{m0}$) of 2.5 m. So, it would be interesting to see the real sea operating performance once the construction is finished.

The construction of the U-OWC prototype was started at the Port of Civitavecchia in 2011 [42]. The 578 m wave energy power plant consists of 124 chambers integrated into caisson breakwaters. One caisson comprises 8 chambers. An early report of the first U-OWC plants can be seen in [35].

### 4.4.5  Siadar Wave Power Project

In 2009, N power proposed a 4 MW wave energy plant, that if finished, would be the largest in the world, located in Siadar Bay, Lewis, Scotland (Fig. 4.9). The proposal was submitted in 2010 as a result of Scotland's ambition to increase its renewable energy production from 50 to 80% of the overall electricity consumption by 2020. A Scottish-based wave energy company, WaveGen (LIMPET's and Mutriku's turbine provider) was then given the opportunity to build the wave power plant. Site measurements were used in a detailed study to establish the design wave condition and optimum orientation of the power plant [22].

As can be inferred from the remote island location, grid connection was one of the main challenges faced by this project. The project needed a subsea cable to connect the electricity produced to the main grid of the UK. The project was delayed due



**Fig. 4.9** Location of the then proposed 4 MW Siadar wave energy converter project, indicated by the red triangle

to the delays in the interconnector and high transmission charges according to the spokesperson for Comhaile nan Eilean (Western Isle Council) in Stornoway Gazette before its ultimate abandonment in 2012. WaveGen subsequently re-designed the project into a 20 MW scheme. Sadly, it did not progress due to continued uncertainty on grid connection capacity and with the abandonment of the revised Siadar Project, WaveGen sadly folded.

### *4.4.6  Floating OWC Development*

The European projects discussed so far have all been fixed structure, either on the shoreline or integrated within a fixed breakwater. Elsewhere, the floating OWC has been explored too. An early example was an open sea test done in Gokasho Bay, Nansei Town, Japan in September 1998. The structure, called "Mighty Whale", was a floating oscillating water column wave energy harvester device consisting of three air chambers. It was tested in an open sea and even endured a typhoon with recorded significant wave height ($H_{m0}$) up to 5.57 m and a significant wave period ($T_s$) of about 12.5 s [44]. Unlike a fixed structure OWC device, a floating body of a floating OWC structure enables the chamber to oscillate along with the water column oscillation and relative to the wave motion. This characteristic makes the mooring system of the whole device to be an integral part of the overall device energy generation efficiency. One significant advantage of a floating OWC, due to the multiple body oscillating motions, is the frequency range at which the device best operates. The structure will have two peak frequencies due to the movement of the OWC chamber and the water column inside the chamber. This allows the device to be tuned to a wider operational range [45].

Another example of a floating OWC was a 1:3 scaled floating OWC deployed in 2010 by Oceanlinx, the then Australian energy company, at Port Kembla, New South. Extreme weather, unfortunately, broke the mooring of the device in the same year of installation although fortunately was still able to be recovered soon after. The company continued to develop a 1 MW energy generator device using the same principle called greenWAVE in 2014 [46]. The completed device, unfortunately, met its end once again after damaged beyond repair during its transport from Port Adelaide to Port MacDonnell. This kind of failure, regrettably, was not unprecedented. In 1995, UK's first offshore wave power plant called Ocean Swell Powered Renewable EnergY or OSPREY 1, which intended to be installed near Dounreay, Scotland, sank to the bottom of the ocean after caught by a 3 m swell of Hurricane Felix. The unfortunate wave energy device was developed by Applied Research and Technology of Inverness. It was concluded that repairing OSPREY 1 was unlikely to be viable and the project was abandoned as reported by the Herald. The most recent floating OWC design took advantage of a cylindrical shape with a tapper-heavy bottom to stabilised the so-called Spar-buoy OWC device [47]. The 1:16 scale prototype of the device has been tested at National Renewable Energy Centre, NAREC, UK, in 2012 and is subject to further optimisation. One of the latest Floating OWC devices is the 5 m in

diameter and 42 m in length floating spar buoy with OWC mechanism inside called the MARMOK-A-5. The 80 tonnes in weight floating OWC is designed to generate as much as 30 kW of power. Initially, the device was developed by Oceantec, but later inquired by IDOM inc. in September 2019. Under the initiatives of the Horizon 2020 European Union project called OPERA, the device was tested in Biscay Marine Energy Platform (BiMEP), near the village of Armintza-Lemoiz in Spain, where the device faces up to 14 m high wave [48].

Although the floating type OWC can be exposed to a more energetic offshore location, integration of an OWC device into a breakwater is the easiest and, so far, the most financially viable option.

## 4.5  Brief Summary of Wave Overtopping Devices' Development Over the years

### 4.5.1  General Introduction to Wave Overtopping Mechanism

Apart from the Oscillating Water Column (OWC) typed Wave Energy Converter (WEC), the Wave Overtopping mechanism is also another strong candidate for wave energy development into commercialisation. In general, the concept is equally, if not more, as simple as an OWC. As the wave passes, the wave overtopped and is collected into a water reservoir and then channeled back into the ocean (Fig. 4.10 with water flow indicated by the arrows). A turbine is then placed inside the channel between the water reservoir and the ocean to generate electricity using the water flow. However, unlike the OWCs, the turbine is constantly interacting with a unidirectional seawater flow under this mechanism. One advantage that the wave overtopping has over the OWC's mechanism is that the uplift force is at minimum when the horizontal force is at maximum [49]. In this case, one can imagine that wave overtopping is relatively more stable to higher wave loads against sliding and overturning when compared to
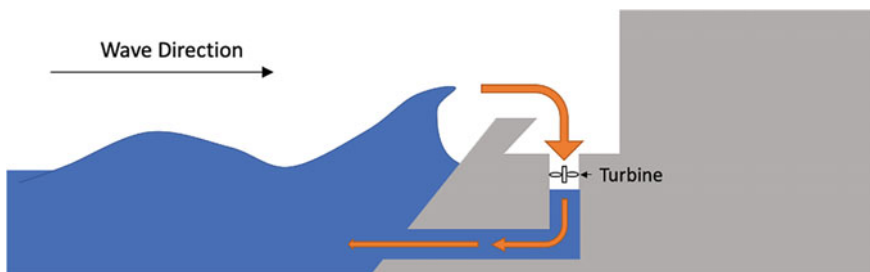


**Fig. 4.10** Schematics of Wave Overtopping energy converters, with orange arrows indicating the flow of the seawater to be collected in the water reservoir and channeled back into the ocean through a turbine

an OWC device. This occurs due to higher wave pressure (commonly associated with higher wave height) resulted in more water being collected inside the water reservoir which in turn provides a larger downward hydrodynamic pressure to counter the uplift pressure. Here the uplift force is defined as the force acting in the upward direction resulted in structure being "lifted" and mostly caused by the combination of buoyancy and turning moment due to wave loads. Although it is less explored compared to an OWC-type device, there were several waves overtopping WEC projects both the floating type, like Wave Dragon and WaveCat, and the bottom standing type, such as the Sea-wave Slot-cone Generator (SSG) and the Overtopping BReakwater for Energy Conversion (OBREC), that gain a lot of attention and gathered a significant amount funding over the years. Here the development of the bottom standing type Wave Energy Converters, the two later projects mentioned, are presented as a brief introduction on the development of such structures.

### 4.5.2　Wave Loadings Analysis and Development of Sea-Wave Slot-Cone Generator (SSG)

In 2004 the Sea-wave Slot-cone Generator (SSG) wave overtopping wave generator concept was developed by WaveEnergy AS company based in Stavanger, Norway. The device, in general, is a multi-stage wave overtopping water reservoir with a multi-stage turbine installed in between the stages to generate electricity. The concept of the device first developed in the idea that using multiple reservoirs would lead to higher overall efficiency when compared to a single water reservoir [50]. This device, furthermore, is intended to be a standalone energy converter standing on a steep foreshore called "*concentrator*" [51] or "*focuser*" [52], which functioned as a way to increase the potential run-up height and also forced the incident wave to break, thus dissipating the incident wave load. The developer managed to secure 5million Euros in funding from both the private sector and European Union to build a prototype in the isle of Kvitsoy-Norway [53]. Shortly after that, another prototype was also planned to be built on the neighbouring West Norwegian Coast of Svaheia [52]. On the initial estimation, the 500 m long device should be able to generate electricity with the cost of about 0.12 EUR/kWh, which is already competitive when compared to the island main power generation source of diesel generators, with further forecast reduction to be as low as 0.04 EUR/kWh once deployed in a larger scale.

The early focus of the SSG's design was on the front wall wave loading. Since wave overtopping requires the incoming wave to overtopped into the water reservoir, the front wall is angled in such a way to increase the amount of overtopping. The SSG itself has 3 reservoirs with 35° inclined front wall on each reservoir stage as demonstrated in Fig. 4.11. To analyse the wave loads, [53] provides the wave forces acting on the front wall of the structure using a 1:60 physical scale model tested in a wave tank at Aalborg University.
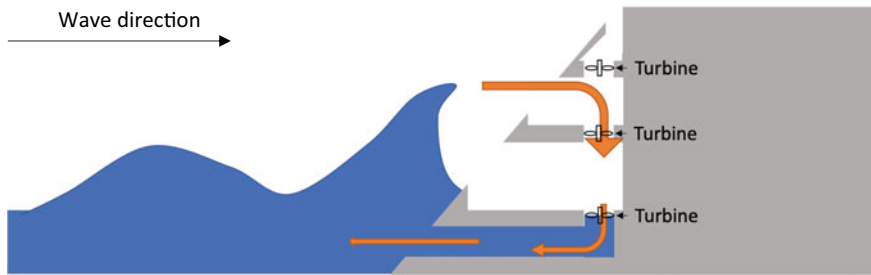
**Fig. 4.11**  A simplified schematics of Seawave Slit-cone Generator (SSG) wave energy device after [50]

Due to the shape of the bathymetry, the study found two types of wave endured by the structure: a surging wave attack to the front wall with no breaking wave (a rapid rise of the wave along the three stages of inclined front wall) and a partially damped plunging breaking which hits the sidewall and resulting in a high vertical jet. The study, furthermore, found that similar trapezoidal pressure distribution as to the one suggested by Goda [20] appeared in the pressure measurement results on each front plate for each stage.

In subsequent experiments, [50, 54] estimated the SSG has about 50% hydraulic efficiency by comparing the wave loads on the front wall of the device and the amount of hydrostatic pressure collected on the bottom of the water reservoir due to overtopping. This efficiency is extracted based on the 2-D study with a wave coming from the front of the device and no spreading occurs before reaching the device location. When exposed to wave spreading, the efficiency is quickly reduced to be between 30 and 25% depending on the angle of the incident wave with efficiency as low as 15% measured during severe unfavourable incident wave angle condition [50, 55]. Further exploration pointing to the water reservoir width: depth ratio to be one of the most determining factors for this efficiency number. It is also interesting to note that impact pressure was observed on both the front wall and the internal rear wall of the physical model. The 35° inclined front wall was designed to "force" the incident wave to pass the breaking wave height, thus dissipating the wave energy. The impact pressure measurement on the internal rear wall, on the other hand, showed that the angle is not optimal to break all of the incident waves.

### 4.5.3  Overtopping BReakwater for Energy Conversion (OBREC) Development

Based on the lesson gathered during the Sea-wave Slot-cone Generator (SSG) development, a wave overtopping device called Overtopping BReakwater for Energy Conversion (OBREC) is currently under development, led by The University of Campania Luigi Vanvitelli or formerly known as The Second University of Naples
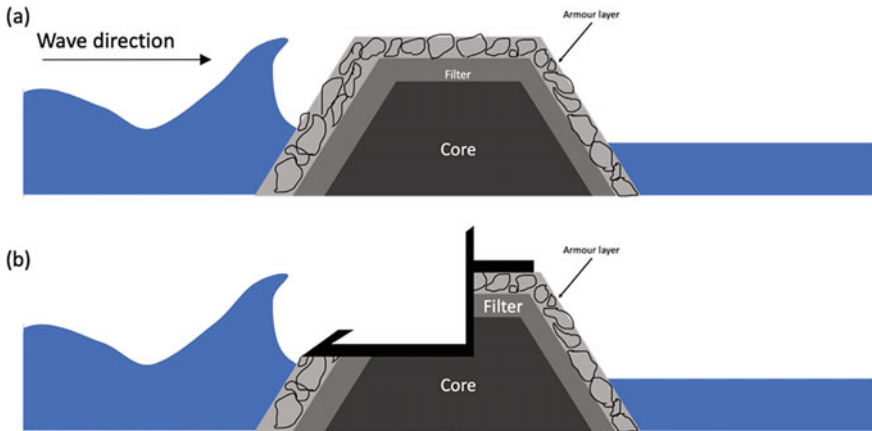
**Fig. 4.12** A simple schematics of a traditional rubble mound breakwater (**a**) and the proposed Overtopping BReakwater for Energy Conversion (OBREC) (**b**) after Vicinanza et al. [56]

[56]. The device takes advantage of the traditional rubble mound breakwater configuration (Fig. 12a) and added a water reservoir sitting on top with a front opening facing the seaward (Fig. 12b). The water reservoir is then connected back into the ocean via a power take-off mechanism.

Early exploration of design suggested that the addition of the WEC increases the stability of the overall structure by providing a counter momentum to the wave loading direction due to the hydrostatic pressure provided by the water collected in the reservoir. The subsequent experiment, however, showed that the inclusion may slightly increase the amount of overtopping water discharged to the rear part of the breakwater, especially in the case where a large amount of water entered the reservoir and created an impacting water jet to the OBREC's rear wall. The same experiment suggested that this problem can be mitigated by adding a triangle on top of OBREC's upper crown wall pointing seaward [57].

When designing a breakwater, the height needs to be determined to be able to balance between the allowable overtopping rate, i.e., amount of water managed to go to the rear part of the breakwater, and the cost and the esthetic of the structure. In such a case, it is more likely that the height of the OBREC should be similar to the original breakwater design to stay in line with the esthetic consideration of the design. To gain more understanding, a prototype scaled version of OBREC was installed at San Vincenzo Breakwater in 2015 [58]. The prototype covered an area of about 75m$^2$ and consist of two different front wall heights. In order to get the incoming wave height, 2 buoys made out of 15 inches in diameter ABS spheres were deployed 100 m in front of the structures. The prototype was originally planned for a 3 year observation campaign and recently the effectiveness of a curved wall to be the front wall is also explored using a small-scale physical model [59]. It is interesting to see the results of the prototype testing once the project has been concluded. Even though the utilisation of wave energy as a renewable energy source has a rough start,

with the inclusion of WECs into several much-needed coastal protection structure projects all around the world, especially when more extreme weather is expected in the future, the future of wave energy development could only increase from now on.

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