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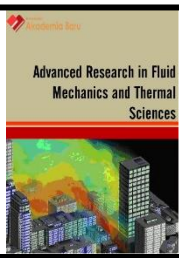


# Wave-Activated Body Energy Converter Technologies: A Review

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**ABSTRACT**

Ocean wave could convert the resource energy more than half of its potential capacity often over time, compared with wind or solar system, which is less than half of its capacity resource. However, the challenge rises on designing an ocean wave-capturing device that can achieve optimum efficiency. This paper addressed several topics including the overview of existing technology of wave energy converter with emphasis on wave-activated body category, current principle of energy harnessing, types of generators utilised to harness the wave energy and the current technologies of power electronics implemented to ocean wave devices. Wave energy converters (WEC) that are commercialised, under testing and still in prototype stage are all listed and divided into two different categories, namely, submerged and floating on the sea. The results reveal that, compared with submerged WECs, the floating WECs gain more attention for development. The key factor in choosing a float on device is to consider the fabrication cost, environmental impact especially for marine life, design and maintenance issue, installation site and the selection of power take-off system.



## 1. Introduction

Nowadays, renewable energy attracts more attention and establishes a field of interest for experts, including government agencies and researchers. Presently, owing to an increase in pollution, rising levels of carbon dioxide and climate change, it is imperative to foster awareness to engage into the green technology development focusing on electrical generation for future sustainability. It is estimated that the industry sector, agriculture, forestry, electricity and heat production account for more than two-thirds of all the anthropogenic greenhouse gas emissions [1]. In fact, about 80% of the world's total use of energy is sourced from fossil fuels, which play an essential role in the stationary energy (including electric power generation) and transportation sectors [2].

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Among renewable sources, the ocean offers huge potential in extracting the usable energy generated from its wave capability. Wave energy represents a promising source for countries with favourable large coastline extension and sea wave climate [3-4]. It has also been reported how this source can offer new areas to be widely explored, which creates important supply chain especially in the energy sector and opportunities in the job sector [5]. The interest in wave energy is widespread almost all throughout the world, as reported by several research and projects in the literature [6]. Also, the worldwide potential of wave power is around 29 500 TWh/yr, harness from on-shore and near ocean shoreline which considered as a small of fraction efficiently extracted [7].

To date, there are two different streams of research: the first one is focused on the designing and development of WECs, and the second one , on the evaluation of sea wave parameters and energy potential, in order to identify areas that are more suitable for the installation of WECs [8]. Initial work in WECs has been explored since 1890 [9] which started from inventing a suitable generator for wave energy harvested in small trials and experimental stage, with few failures. Decades after, the research on WECs continues with a different perspective, some of which is still in concept and prototypal stage and only a few have been tested extensively in an open sea [10]. For example, Thorpe discussed the potential of WECs depending on economic reviews, Lysekil project, Norwegian heaving buoy and Swedish heaving buoy, and so-called L10 of Oregon University has developed prototype devices for wave energy harvesting [11].

The technical challenge arises upon development, especially in estimating the electrical power output, since the wave generation in terms of its height and interval period from crest to crest is intermittent and irregular. Therefore, this nonlinear characteristic of motion will create different kind of frequency and amplitude pattern of electricity, fluctuation and noise, hence, facing difficulties to directly synchronise the generated electricity to integrate it with the main grid line. For solutions, some approaches require the implementation of control strategies within the hardware architecture, designing of an optimal electronics controller device or installation of an energy storage system to stabilize the electrical production. However, to implement the proposed ideas will be very costly especially establishing the physical system. Besides, most of the works of literature on control strategies not experimentally verified. Moreover several WECs device are still in the development stage with only some projects having reached demonstration status and a few closing for commercialisation [12].

WECs can be classified into several categories [6]. This paper discussed the device working principle on the basis of the capturing system and divided it into three major categories. Also, the electrical part of Power Take-Off (PTO), including generator types and power electronics technologies, and device technology, specifically focused on wave-activated-body category, has been deliberated in detail.

## 2. Classification of a WEC

In general, WEC can be classified based on location (onshore, near shore or offshore), working principle with respect to the type of PTO used on the WEC (hydraulic, electric or turbine, mechanical drive system and direct electrical drive system) or classifying with regard to the working principle in capture system [13]. The capture system category can be divided into three main types namely, Oscillating Water Column (OWC), Overtopping (OT) and Wave-Activated-Body (WAB) [14].

### 2.1 Oscillating Water Column

The working principle of the OWC is by manipulating heave motion of waves in special air chambers. The air trap inside the chamber will create air compression and decompression driven by the wave movement upwards and downwards, which is forced to flow through the turbine and drive the generator to produce electrical power. The chamber can be fixed inside an onshore structure or installed in a floating buoy [15-16].

The air flow will move outwards when the water in the chamber move in upwards directions and conversely, the air flow suck back inside the chamber when the water level was moving downwards as shown in Fig. **1**. The phenomenon will create bidirectional air flow movement and thus, push the turbine to rotate in both directions either clockwise or counter clockwise. This kind of rotation is inefficient in harness optimal wave energy; hence, to solve the issue, the Wells turbine was invented in the mid-1970s [17-18], and it is most frequently proposed to equip with OWC plants. The self-rectification induced caused by an axial flow turbine was not sensitive to the air flow direction for the torque response. Consequently, an improvement has been made by Babintsev by proposing a self-rectifying impulse turbine [19].

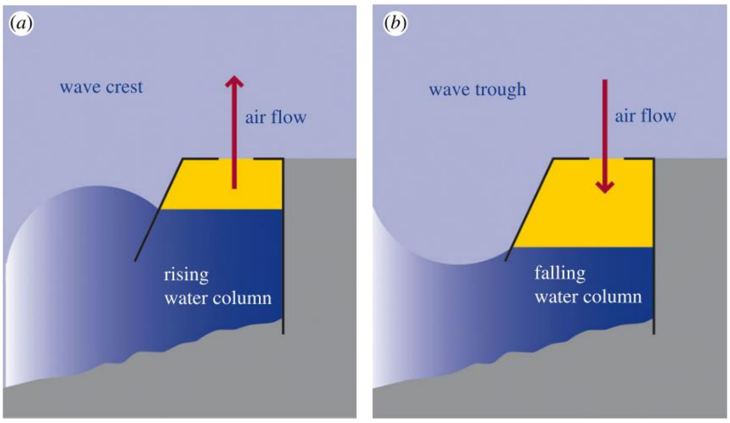



**Fig. 1.** Principle of OWC [20]

The technologies of OWC types have been discovered and patented since the early 19$^{th}$ century by J. M. Courtney with his invention named as whistling buoy, which is used for navigational buoy system [20]. In 1947, Masuda *et al.,* [21] designed and installed the first OWC driving an impulse turbine to produce electricity for powered navigation lights with the system in combination with rechargeable batteries. In 1978-1986, Kaimei was the first OWC floating device deployed at the coast of Yura, Tsuruoka City, and the construction consist of eight chambers installed in the huge mooring barge floating on the ocean, capable of generating 125 kW of power rating [22]. In the 1990s, the first OWC integrated with the breakwater was built at the port of Sakata, Japan, where the five-chambered OWC was constructed with the tandem wells turbine as the PTO system, which is capable of producing power of approximately 60 kW [23]. In 2000, The Land Installed Marine Powered Energy Transformer (LIMPET) produced the world's first WECs that can harvest the wave energy and supply directly to the grid [24]. The installation has been made an onshore site at Islay, Scotland, which is capable of generating 500 kW at the beginning, estimated to sufficiently supply around 400 houses at the targeted island. However, after 7 years of continuous grid-connected operation, the capacity was later downgraded to 250 kW, providing an additional test space for newer turbine development. Finally, in 2018 the plant reported has been decommissioned [25].

### *2.2 Overtopping*

The principles of OT are based on docks that are refilled by waves, and particularly the water stored in the reservoir, as shown graphically in **Error! Reference source not found.**. During wave propagation, the ramp placed faced to the incoming wave. Thus, the wave led up a ramp and was collected in the reservoir. Technically, the level is higher than the current ocean level. The turbine was installed underneath the huge reservoir. The potential difference of ocean level will create a gravitational force to allow water flow downwards back to the ocean. Then, the water flow stream in return will rotate the turbine to generate electricity.

In OWC development, two criteria should be considered in achieving the success: the targeted site and the design of the OWC. The detail analysis of the potential site, including annual distribution of wave frequency and wave height, should be carried out to ensure that the device is capable of operating optimally along the years without resource interruption. For the design aspect, proper analysis is necessary, including crest freeboard (height of the ramp crest above mean water level), reservoir sizing (if the reservoir is overfilled when a large volume is deposited in the basin there will be loss caused by 'spill' issue) , and hydraulic power converted by the turbines (effect from turbine flow, the head across them, water density and gravity) [26].

Among the OT technologies initially discovered during the 1980s is the Tapered Channel Wave Power (TAPCHAN) [27] with power rating of 350 kW and the installation has been made onshore at Toftestallen, Norway. In 1998, the company set up the TAPCHAN plant with a capacity of 1.1MW at Indonesia island of Java. In 2003, the Wave Dragon was the world's first device that proposed OT principle on offshore site, where the prototype device has the potential to harness power rating of 140 kW [28]. The Wave Dragon was forged ahead by currently supplying 7 MW of electricity to Wales grid and is underway to be set up offshore at Portugal with an estimated power generation of about 50 MW [29].

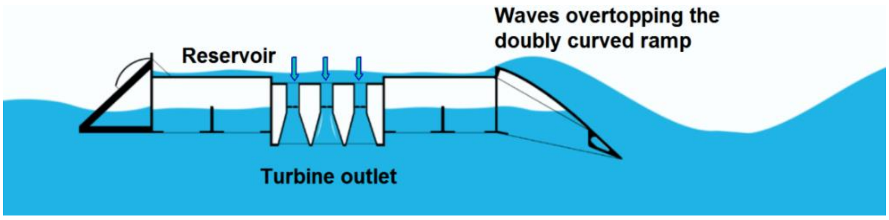



**Fig. 2.** The scheme of overtopping principle [30]

### *2.3 Wave-Activated-Body*

The WAB working principle will be based on the manipulation of waves elevation or wave propagation characteristic by driving the WEC mechanism (usually buoy) and, in return, the kinetic energy will be converted to electricity. The WAB principle can be mainly categorized into two, as depicted in **Error! Reference source not found.**, namely, essential translation (point absorber) and essential rotation (hinged) [6]. The installation for this WEC device principle can be at the sea floor (submerged) or floating on the sea surface.

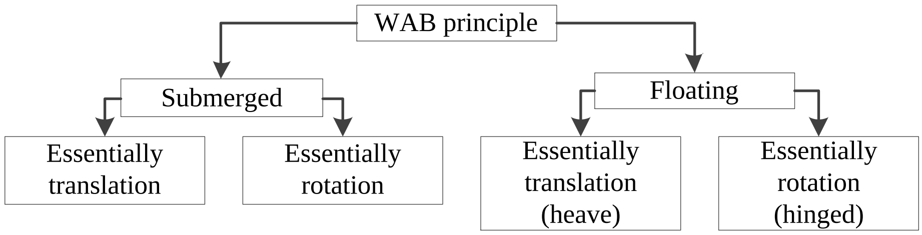



**Fig. 3.** WAB sub-categorized

The essential translation device, generally, has a huge vertical structure ratio compared with horizontal body ratio. It completely harnesses the wave energy focusing on a single point absorption of wave heave motion. Usually, this device category is installed vertically, and during the wave rise and fall, the effected float buoy will move simultaneously inline, and the converter system forces the generator to produce electricity. The damper structure is mooring to the seabed for the floating device type to remain in its position or to lie on the seabed floor so that it is completely submerged. This device was usually working at the offshore site, where the powerful wave potential can be exploited to maximize device productivity. Since it is far from the land, the generator is integrated to the device, and if it consists of multiple devices, the electrical production from each device will be integrated to the main centralised system installed onsite and then connected to the on-land grid by using standard long distance submerged cable.

For essential rotation device, the most submerged type is more on utilising the wave propagation back and forth to activate the WEC system. For the design of submerged type, the horizontal body ratio of the device is usually huge compared with the vertical body ratio. The design of the device in general consists of two main structures. The first structure is to hold the converter system and act as a foundation for the overall structure. It lies on the seabed or is partially submerged in the water. The second structure will be connected to the first structure with a hinge mechanism so it can flex and free float upwards.

The placement of the device faced the wave propagation, and as the waves pass through the device, the second body considered as a buoy will flap and allow the converter system to run the generator. Meanwhile, for floating device type, the WEC system will exploit wave elevation activity to run the generator. The floating device type is typically designed in a multi-section structure inherently arranged parallel to the wave propagation. The flexible joint or hinge linked between the sections allows the device to flex the structure and remain in place by a mooring mechanism. As the propagated waves pass through the length of the device to provide different height and enable section bend, the flexing joint is linked to the converters and finally allow the generator to function. This floating type device usually installed offshore where the wave regime is so promising to guarantee that the device will work optimally.

### *2.3.1 Submerged WEC technology*

In 2004, the Archimedes wave swing (AWS) deployed off the northern coast of Portugal, essential translation-type device submerged on the sea floor (43 m underwater) that is capable of generating 2 MW of power [31]. The system consists of two main parts, silo (a bottom-fixed air-filled cylindrical chamber) and the floater (a movable upper cylinder) [32]. The floater heaves due to changes in wave pressure, as shown in **Error! Reference source not found.**. The floater moves downwards compressing the air inside the structure when AWS faces under a wave top. Meanwhile, the pressure from outside decreases when AWS under a wave trough and force the floaters moves up due to air traps inside the structure expands [33]. This continuous phenomenon will cause the Electrical Linear

Generator (ELG) to convert the motion into electricity. The AWS can hence be expected to behave much like a mass-spring-damper system, though with relevant non-linearities [34].

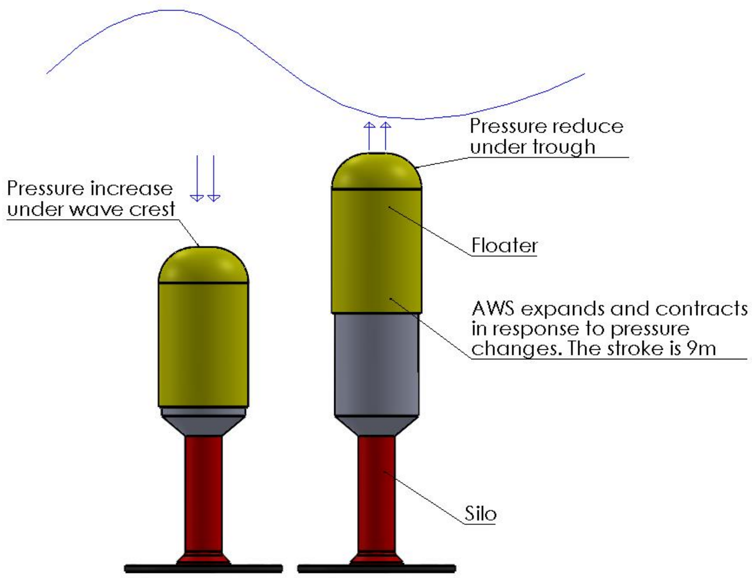



**Fig. 4.** AWS working principle [31]

A device named as CETO (named after the Greek goddess of the sea) is developed by an Australian company, fully submerged and deployed off the coast at Western Australia [35]. The structure comprises huge buoys that move accordingly upwards and downwards due to ocean wave, as illustrated in **Error! Reference source not found.**. The capture of movements will drive a piston pump located on the seabed floor tethered directly to the buoy. The pump, in return, delivers high-pressure water through the pipeline to an onshore facility and drive hydraulic generators. At the same time, the water pressure flow is used to run a reverse osmosis desalination plant.

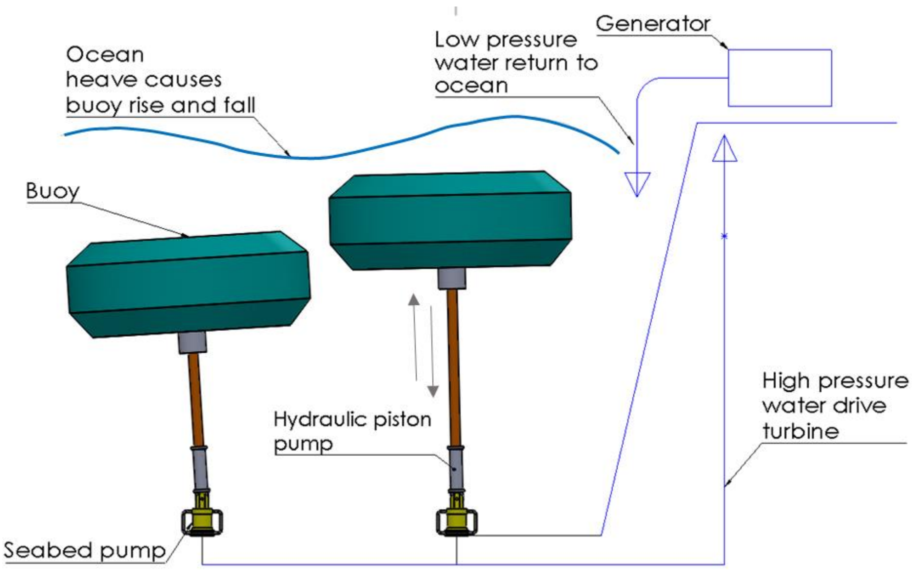
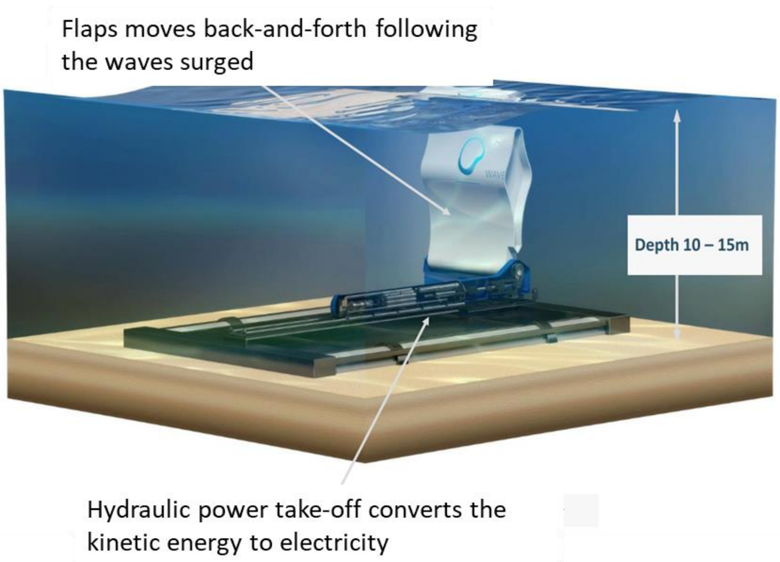



**Fig. 5.** CETO floating submerged [35]

Another submerged technology device is the WaveRoller [36], which implements different approaches in harnessing the wave energy. As shown in **Error! Reference source not found.**, the device consists of a plate (flap) anchored with mechanical hinged on the bottom sea by its lower part. Back and forth activities of the bottom wave will hit the flap and force it to move, and the kinetic energy produced is used to run a piston pump from hydraulic motor. This form of energy is later converted to electricity with a combination of generator system attached to the hydraulic motor. The device reported it still in the development phase and targeted to be installed on the sea floor near-shore areas with a depth of between 8 and 20 m. It reported to harness the electricity for about 350 kW to 1 MW [37]. The bioWAVE device has similar working principal with WaveRoller; instead of using flap-shape design to capture wave motions, this device use cylindrical structures. As the ocean water accelerates and decelerates around the cylinders with each wave, the structure responds by swaying similarly as a pendulum, resulting in a large, but varying and reversing, torque (or moment) about the pivot axis [38]. The hydraulic system will deliver high-pressure fluid to the O-Drive module to convert irregular hydraulic energy into AC electricity.



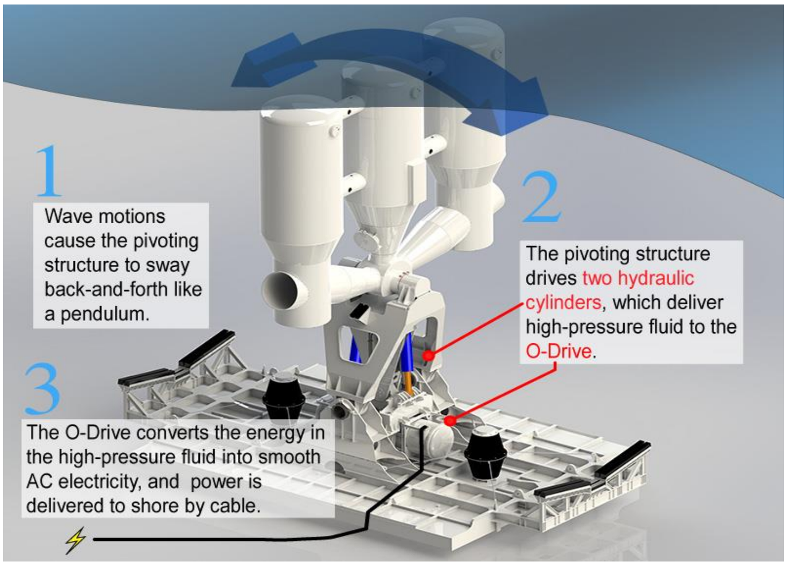




**Fig. 6.** WaveRoller [36] (top) and bioWAVE [39] (bottom) working concept

The Oyster wave energy converter device developed by Aquamarine Power [40] is another device that used similar mechanical hinged design and the flap is partially on the sea surface.

shows the working concept of the WEC. Rather than using hydraulic oil, this device transfers high sea water pressure from the piston pump to the onshore plant via the pipeline. Later, the high-pressure water will force the Pelton type turbine, which generates electricity. In 2009, the device was launched in the Orkney region in Scotland and was estimated to generate 350 kW of power [41].

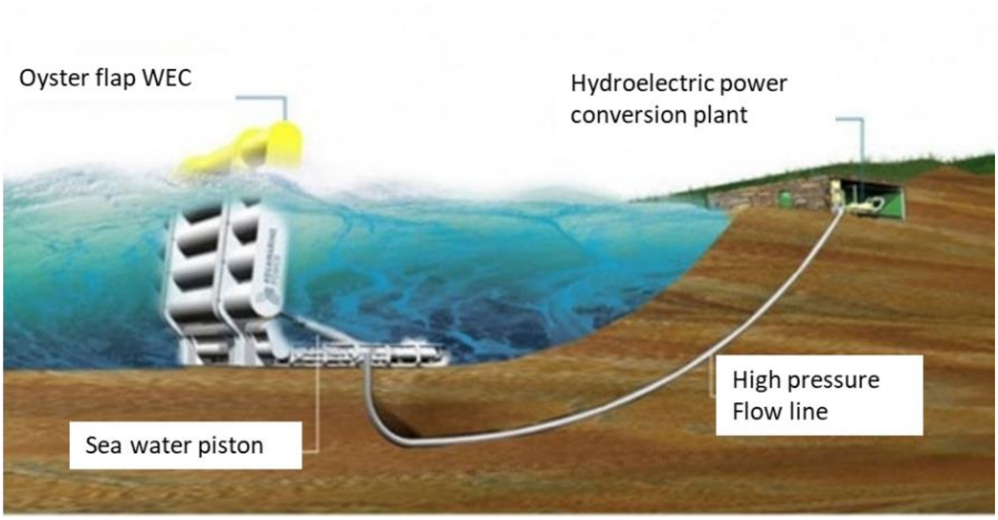



**Fig. 7.** Oyster WEC [40] working concept

Rather than using float type as a WEC system, RivGen [42] proposed a different mechanism by using turbine generator unit, consists of two turbines linked through a single driveline to an underwater generator located at the centre of the structure. The targeted area for deployment of this device is at the remote river and a coastal community area where the strong current of water as a resource to power the generator. The device is submerged on the riverbed by facing the tidal current. The current flow will force the turbine to rotate and then transmit to the generator for produce electricity. Next, the electrical power is transmitted to the onshore with the interconnection point. Table **1** summarized the list of the abovementioned submerged WAB device including the PTO configuration, installation location and power capacity of generation.

**Table 1**
List of submerged WAB devices

| WECs | Year | Installation type | PTO system | Location | Capacity | Refs. |
|---|---|---|---|---|---|---|
| ArchimedesWave Swing (AWS) | 2004 | ET | DEDS | Northern coast, Portugal | 2MW | [31] |
| CETO | 2014 | ET | HS | Garden Island, Australia | 400kW | [43] |
| WaveRoller | 2014 | ER | HS | Peniche, Portugal | 300kW-1MW | [36] |
| Oyster | 2009 | ER | HTS | Orkney,Scotland | 300-600kW | [40] |
| RivGen Power | 2014 | ER | HTS | Alska, USA | 25kW | [42] |
| bioWAVE | 2015 | ER | HS | Port Fairy VIC Australia | 250kW | [44] |

### *2.3.2 Floating WEC technology*

Floating WEC, which generally utilises the heave and the surge motion of waves is presented in **Error! Reference source not found.**. There are two main techniques of the mechanism used to harness the wave energy: (i) essential translation (point absorber) and (ii) essentially rotation (linear absorber). The essential translation device can be separated into two categories that are based on its installation technique, which is either its bottom fixed part is floating submerged or lies stationary on the seabed.

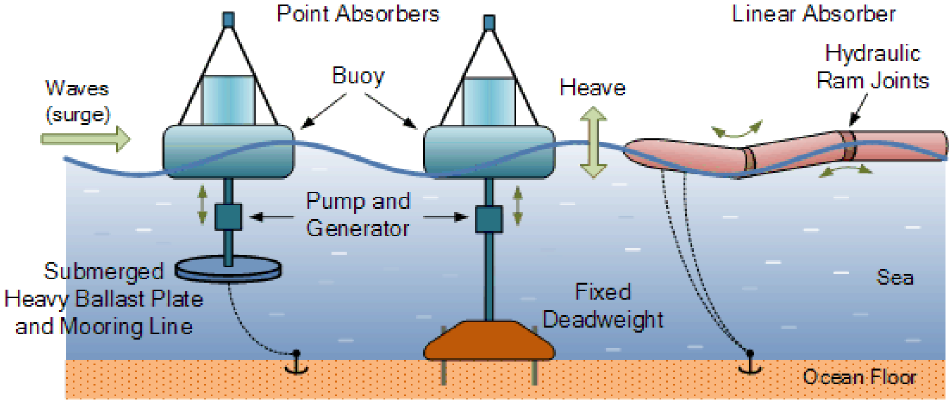



**Fig. 8.** Wave-activated-body principle for floating type [45]

The well-known floating type device with the approach of essential rotation (hinged), a prototype Pelamis, was first deployed during 2004 and electricity produced by this device was linked to the UK grid with rated of power production of about 750 kW [46]. The device was constructed with five large tubes joined each of them with the approach of flexible hinged, float semi-submerged on the ocean surface, as shown in **Error! Reference source not found.**. As the waves pass down the length, the affected joint will bend and activate few arrangements of the hydraulic cylinder inside each section tubes and thus run the generator coupled with a hydraulic motor to produce electricity. In 2008, improved version model of P1 Pelamis was set up at northwest coast of Portugal and become farm first generated electricity, which is capable of producing electricity of about 2.25 MW in total [47], followed by P2 Pelamis which is wider, longer and heavier than the previous version allowing the device to capture more energy while substantially reducing the cost per power production [48]. [49] claimed that the Pelamis responds to wave curvature only instead of wave height and restricts the range of motion when the waves naturally get longer as they get higher.

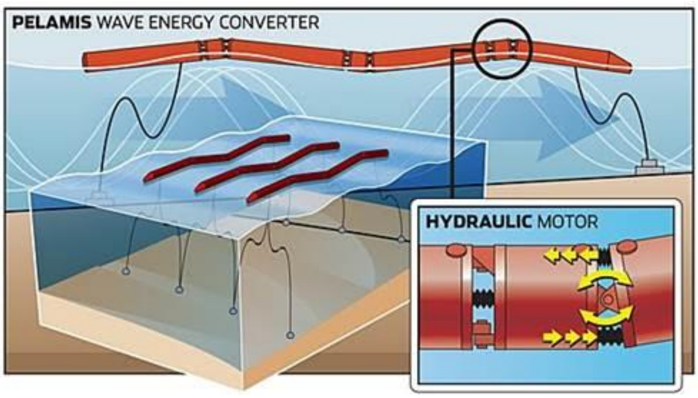



**Fig. 9.** Configuration of Pelamis WEC [50]

The Volta WEC used the same working principle as WaveRoller in capturing mechanism and comprise with multi-connection of the WEC system unit. However, the Volta WEC partially floats on the sea surface instead of fixed on the seabed [51]. The nine units of the PTO system as illustrated in **Error! Reference source not found.**, encompasses with the arrangement of flaps and hydraulics cylinder, connected with long tube float submerged and mooring on the sea floor. The device development used almost light materials from High-Density Polyethylene (HDPE), which claimed to be able to help reduce concentrated stresses and produce extremely cost-effective WEC [51]. However, there is no report about the capability of the WEC in terms of energy production.

**Fig. 10.** The Volta WEC arrangement on the ocean [51]

The Wavestar WEC draws energy from wave power with the arrangement of floats that rise and fall with the heave motion of waves [52]. **Error! Reference source not found.** shows that the arms attach the floats designed in semi-sphere shape to a platform that stands on legs secured to the sea floor. Waves run the length of the device, lifting 20 floats in turn. The motion of the floats is transferred via hydraulics cylinder into the rotation of a generator, producing electricity. Based on the feedback, the arrangement of multi-floats optimally utilises every single incoming wave high, which passes through the floats, thus providing a smooth output to the generator and enables continuous energy production. The Eco Wave Power device also has similar working principal with Wavestar; instead of offshore installation, this device decided to takes a different approach by installing the device in the onshore and near shore environment to prevent high cost installation, avoid disturb local marine habitats in the ocean floor caused by mooring system and the offshore ocean climate are often extremely harsh potentially to damage the device [53].

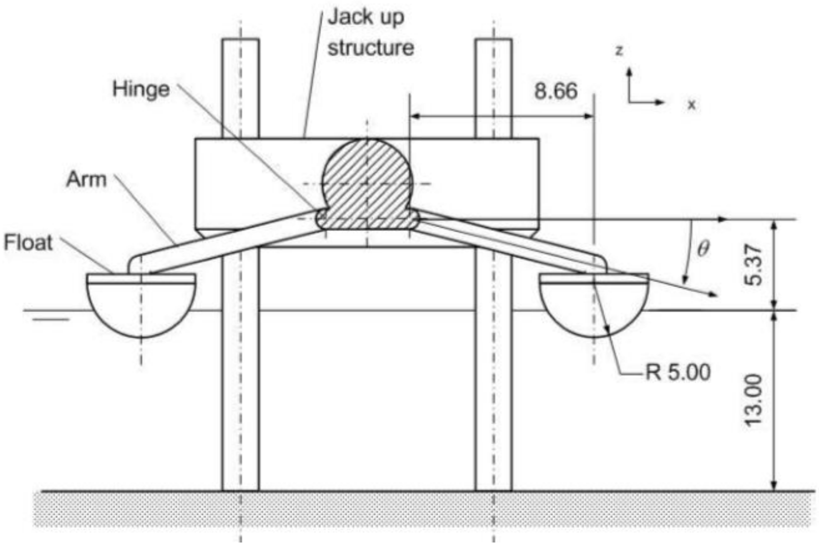



**Fig. 11.** Wavestar floats arrangement [52]

The Azura WEC is another essential rotation type of floating device that claimed able to extracts power from both wave regime, heave (vertical) and surge (horizontal) motions to ensure the maximum output power can be captured [54]. The mechanism consists of relative rotational motion between the float and the hull. As shown in **Error! Reference source not found.**, the huge floating structure named as PowerPod consists of two large cylindrical structures that stand vertically. It will hold the float structure at the middle point of the Powerpod through the crankshaft. The PTO system located at the upper section of the Power Pod comprises hydraulic motor and accumulator. Two hydraulic cylinders located at the bottom section of the PowerPod are linked to the eccentric shaft. The advantage of Azura is that the energy can be harnessed from the hull motion. In which either it oscillates back and forth, or the float is rotating continuously through 360°. The propagated waves pass through the device, causing the motions for both float and hull, and then drive the hydraulic cylinder system. The pressure from the hydraulic cylinder has been accumulated and later used to drive a variable displacement of a hydraulic motor, consequently driving an electrical generator to produce electricity [54].

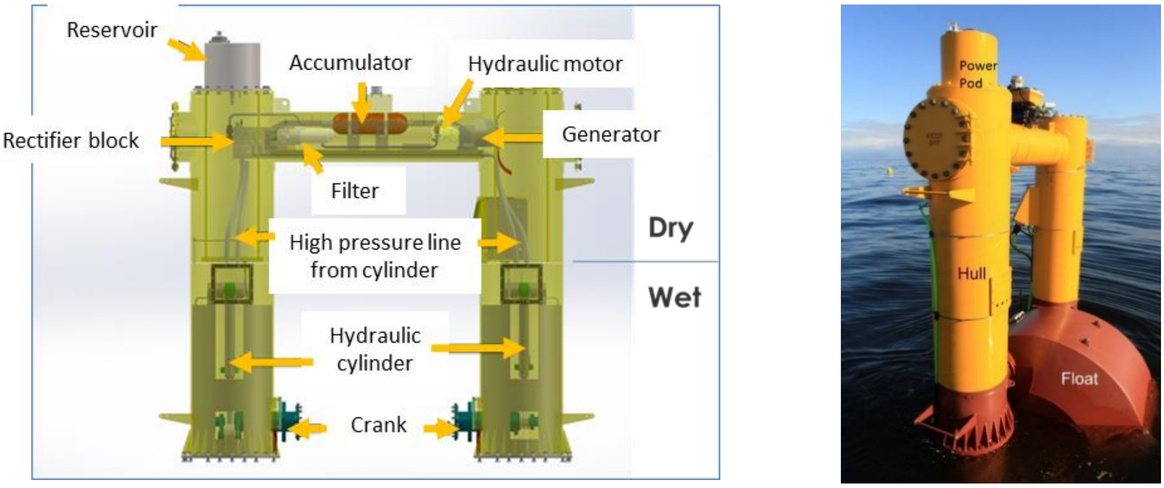



**Fig. 12.** PowerPod structure of Azura WEC [54]

The Wavebob is an essential translation type, in whichthe main structure consists of two heaving buoys with the first buoy known as  a float linked with a 40 m draught placed at the centre of the system with the buoy completelyfloating above the sea level [55]. **Error! Reference source not found.** shows crucial key component of this WEC [56]. Meanwhile, the second buoy is placed around the first buoy like a floating cylinder ring named as a torus tank, 14 m in diameter. The three-unit hydraulic cylinders act as the PTO system, connected in between the first and second buoys at the upper section, as the waves heave, allowing three degrees of freedom of movement between two oscillating buoys. The power collected by hydraulic cylinder from pitching and rolling motion, linked to the hydraulic motor and finally rotates the generator to produce electricity [55]. The capacity power generation is about 500 kW for the individual unit, which is estimated to provide enough power within 300 to 400 households every day [57].

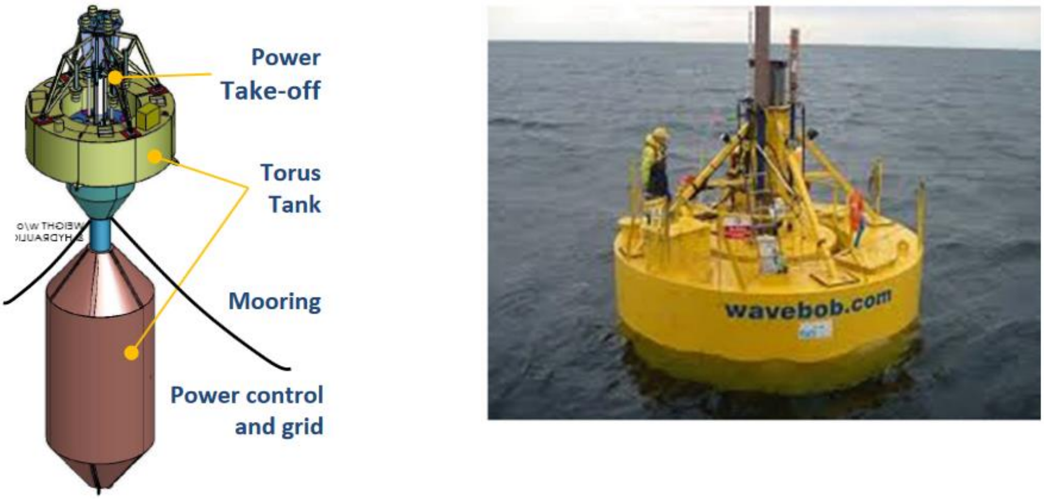



**Fig. 13.** Key component of Wavebob [56]

The AquaBuOY is another device that utilises wave heave motion. Instead of using hydraulic piston, this device uses neutrally buoyant disk that acts like a giant piston to pressurize the seawater to drive a turbine generator [58]. The vertical floating buoy is connected to the long tube beneath the buoy, and as the floating buoy heave, the buoyant disk will pump the seawater, which passes through the turbine placed on the top side of the structure through the hose. As reported by [58], the prototype device was sunk 7 weeks after being deployed due to some technical problems with the floatation section where the bilge pump was unable to cope up with the system and caused malfunction.

Similarly, the WaveEL WEC consists of the buoy with a long vertical tube underneath it with an open end at both sides [59]. There is a huge water piston inside the tube that will act as a gigantic pump. As waves raise and lower the buoy via the attached tube, they will move differently from the water column within. Instead of using a turbine generator, the water piston connected to a hydraulic conversion system and in return activates the generator. The IPS OWEC Buoy [60] proposed the same principle as used in WaveEL device, the buoy with 3 – 4 m in diameter is placed in position by an elastic mooring enabling it to move freely upwards and downwards against dampening water located underneath in the long vertical tube named as acceleration tube. The relative motion created by the buoy and water mass converted to the electric energy caused by the working piston inside the acceleration tube that passes through the hydraulic system connected to generator unit placed inside the buoy hull [60]. The PB3 and formerly known as PowerBuoy is another floating device with non-fixed bottom end and developed by Ocean Power Technologies [61]. The construction involves a cylindrical structure with one component relatively immobile as the bottom end, and a second component with movement driven by wave motion as the top end floating buoy inside a fixed cylinder. As illustrated in **Error! Reference source not found.**, the relative motion will force the mechanical ball screw moving upwards and downwards and in return, rotates the drive shaft attached to the generator [62].

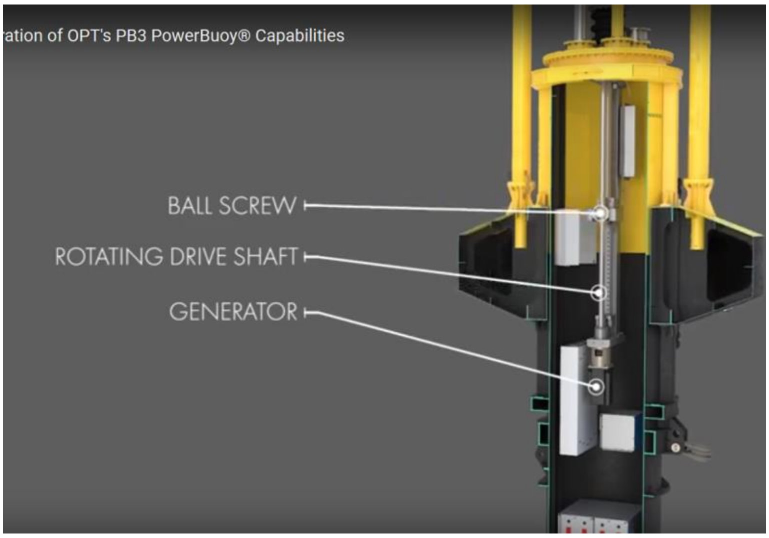



**Fig. 14.** Mechanical design inside PB3

The Oceanus 2 works as float moving up and down synchronously with the waves and then activates a pump built inside the structure to pressurise seawater, which is then channelled ashore with the pipeline to drive a hydroelectric turbine to produce 162 kW of power [63]. The Oceanus 2 with hexagon ring shape buoy is tethered to the block located on the seabed. The device is still in a testing stage where the deployment is about 16 km off the coast, which consumes long-distance pipeline [64]. There is no report about the device capable of running the generator, instead of successful collecting the pressure and flow data along with environmental parameters to build up an accurate model for predicting year-round energy production [65]. Based on observation, the multi-device of Oceanus 2 should be installed to ensure that the hydroelectric turbine received enough water pressure to operate. Similarly, the concept of the tethered buoy is implemented to the Seabased technology device. However, the approach of PTO system is different; as depict in **Error! Reference source not found.**, the Seabased technology used direct linear generator attached to the affected buoy to produce electricity. The Lysekil project device is also proposed to use a linear generator to generate electricity without the intervention of another mechanical loading, and it is directly tethered to the floating buoy located on the sea surface. As the waves heave, the buoy will move upwards and downwards, and the linear generator starts to generate electricity. The HiWave-3 project implemented tension mooring system and anchor bracket attached to an existing gravity-based anchor. Instead of using rotating ball screw shaft as in PB3, this device used cascade gearbox inside the floating buoy. It claims to efficiently convert linear motion into rotating motion by dividing a large load onto a multiple small gears that allow highly efficient and robust conversion [66].

The Triton WEC developed by the Oscillica Power Company is another floating device that uses tethering buoy [69], a buoy floating on the surface of the ocean that contains the generating apparatus of alloy bars, magnets, and coils, as well as sets of hydraulic rams that can squeeze the bars. As shown in **Error! Reference source not found.**, the 1:50 scale of physical model has been set up to evaluate the performance. The system was patented, and the generator named as Magnetostrictive Generator. Such a linear generator type is applied to the system [70]. The cables connect the buoy to a heave plate maintained in a stationary position. As the buoy rises and falls with the waves at the surface and the heave plate stays still, the tension on the cables increases and decreases. The changing tension drives the rams and produces electricity [69]. However, there is no report regarding the full-scale device capability to produce power for this new patented PTO system.

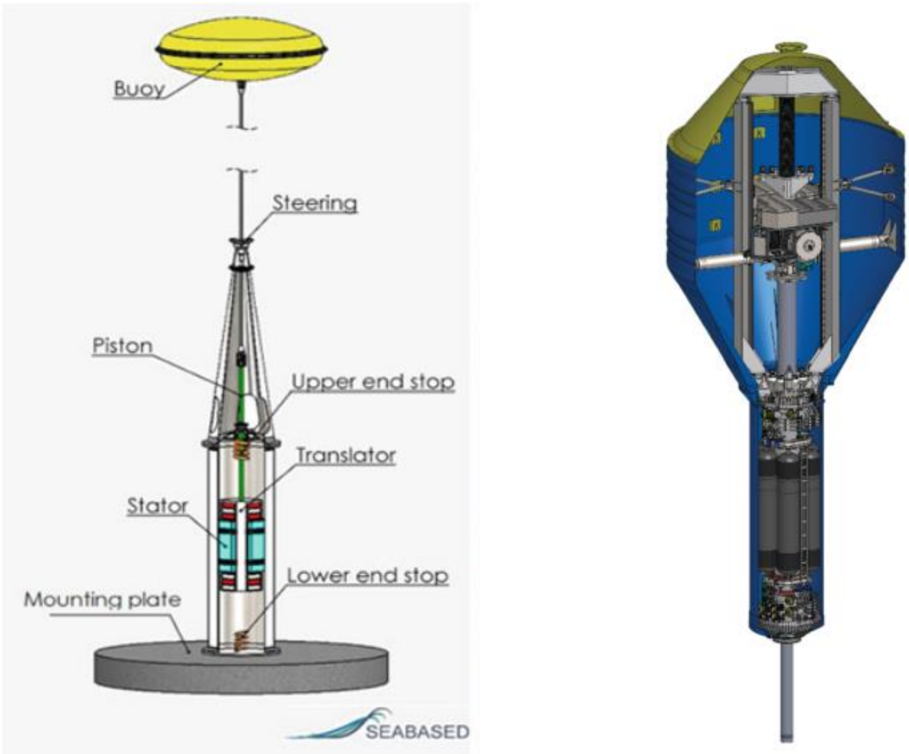



**Fig. 15.** Seabased with a driven linear generator [67] (left) and cascade gearbox inside HiWave-3 [68](right)

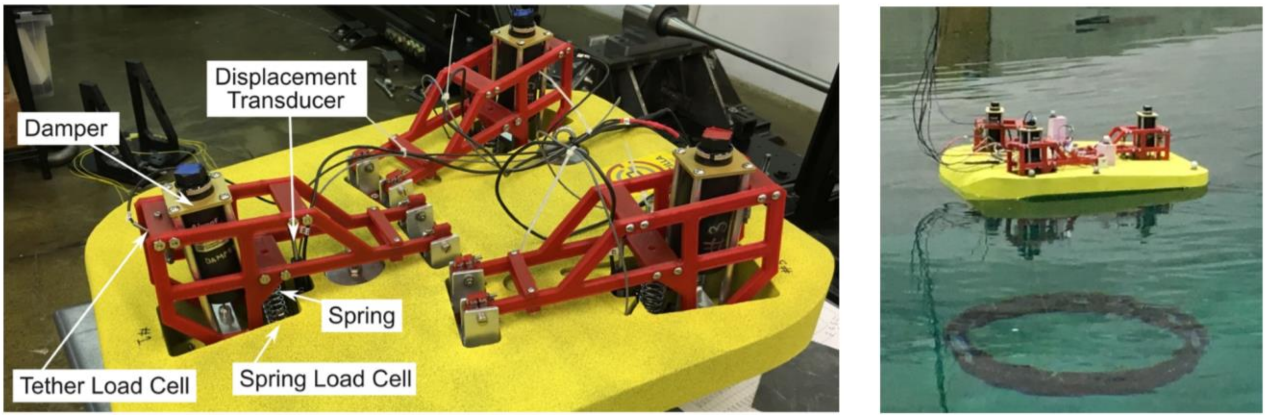



**Fig. 16.** Triton WEC in 1:50 scale physical model with PTO arrangement [71]

BOLT Lifesaver consists of floatation hull with circular ring type with 16 m in diameter as depicted in **Error! Reference source not found.**. The PTO system comprises of a high cycle winch, a belt drive gearbox and an actively controlled generator. The winch line is moored to the seabed at one end and another end line is wound around a drum. As the PTO displaced caused by the wave crest, the winch line is tensioned and inflicts a torque on the drum. Through a gearbox, a generator provides a torque that results in a controlled winch line tension. During the transition from wave crest to trough, the generator operates as a motor to wind the line back in with a controlled tension and the line will always be in tension for the next wave crest. The floating hull is capable to support five PTO unit. However, only three PTO units are assembled, generating a total of 30 kW at the nominal wave condition. Table 2 shows the summary of the available float on WAB devices, and essential translation type of devices is more preferred than essential rotation type.

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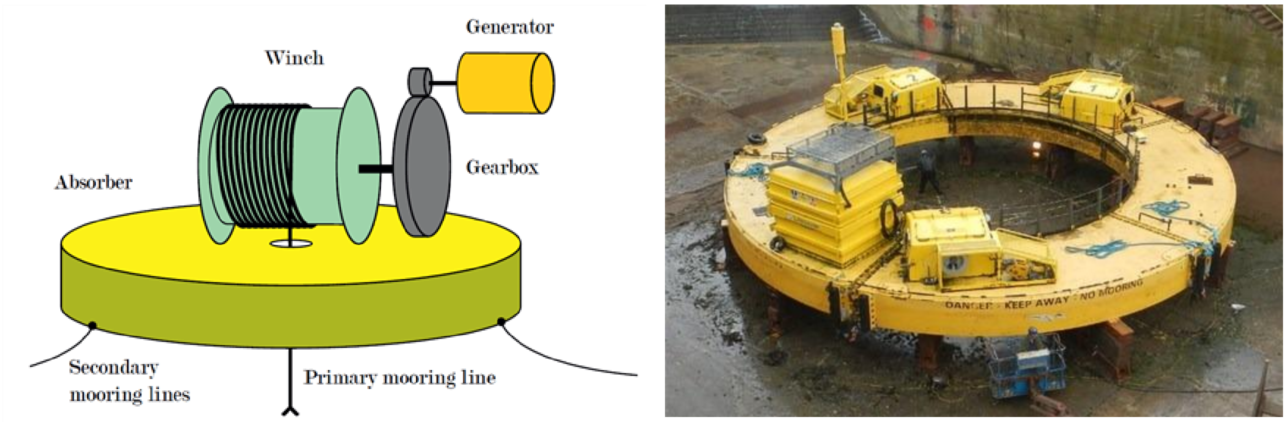


**Fig. 17.** The specification of BOLT Lifesaver WEC, the diagram of PTO system (left) and the floatation hull consist of five sections (right) [72]

**Table 2**
List of floats on WAB devices

| WECs | Year | Installation type | PTO system | Location | Capacity | Refs. |
|---|---|---|---|---|---|---|
| Eco Wave Power | 2015 | ER | HS | Jaffa Port, Israel | 100kW | [73] |
| HiWave-3 | 2018 | ET | DMDS | Orkney,UK | 25kW | [74] |
| BOLT Lifesaver | 2016-2018 | ET | DMDS | WETS, Hawaii | 30kW | [72] |
| | 2012-2014 | | | Falmouth, UK | 2.2-22kW | [72] |
| PB3 | 2017 | ET | DMDS | Kozu Island, Japan | 3-7.5kW | [61] |
| Wave Star | 2009-2010 | ER | HS | Hanstholm,Denmark | 6000kW | [75] |
| Wavebob | 2007 | ET | HS | Galway, Ireland | 500kW | [57] |
| Pelamis P1 | 2008 | ER | HS | Northwest Coast,Portugal | 2.25MW | [41] |
| Pelamis P2 | 2010-2014 | | HS | Orkney,U.K | 1.5MW | [76] |
| Azura | 2012 | ER | HS | Oregon,USA | | |
| | 2015 | | | Hawaii, USA | 20kW | [54] |
| Seabased Technology | 2014 | ET | DEDS | Ada Foah, Ghana | 400kW | [77] |
| | 2015 | | | Kungshamn, Sweeden | 1MW | [78] |
| Lysekil WEC | 2004-2013 | ET | DEDS | Lysekil, Sweden | 30kW-1MW | [79] |
| Triton | 2017 | ET | DEDS | New Hampshire,USA | - | [69] |
| Oceanus 2 | 2016 | ET | HTS | Cornwall, U. K | 162kW | [63] |
| AquaBuOY 2.0 | 2007 | ET | HTS | Newport, Oregon | 1MW | [58] |
| Volta | 2015 | ER | HS | Falmouth, U. K | - | [80] |
| WaveEL Buoy | 2016 | ET | HS | Runde, Norway | 0.2MW | [59] |
| IPS OWEC Buoy | 1996 | ET | HS | Bettna, Sweden | 10 - 150 kW | [60] |

## 3. Generator Types

In WEC technologies, there are two types of generator currently used to harness the wave energy, namely, rotary type and linear translation. Figure shows five different configurations of PTO that linked with these types of generators. The design of the WEC itself will determine which type of generator suits in, and several factors should be considered, in terms of location (shoreline, onshore or offshore), either floating or submerged and type of PTO used in the device. In the OT and OWC devices, the type of rotary generator is always a perfect matched candidate in selection. According to the OWC principle of working, the device will be based on utilising the air flow moving inwards and outwards to spin the air turbine where the generator technologies applied similarly used in harvesting wind energy, but it use different design of the turbine blades.

Meanwhile, for the OT principle, the use of the generator and hydro turbine imitates the technologies applied to the hydroelectric dam where the pressure of water flow will force the turbine. However, the rotary type of generator is not always a perfect match for the other WEC types prior for WAB principle, and it became a major challenge, since the main technique to harness the energy is using an approach of heaving motion and nodding-type devices. The use of simple connection to the rotary generator is no longer compatible for the proposed design that comprises a complex mechanism for its PTO system; hence, the installation of an intermediate system including transmission or hydraulic system, direct mechanical drive system and other types of generator should be considered [81]. The next subtopic will discuss both types of the generators that currently used for the most WECs, including the functions and available technologies.

### *3.1 Rotary Generator*

Recently, the rotary generator is widely used in providing the electricity to the grid either hydro or wind plant. The efficiency and effectiveness of this generator are proven and guaranteed. In general, the operation of this type of generator virtually runs at a constant speed, providing synchronous frequency and amplitude to the main grid. In real wave energy applications, the rotary generator cannot self-harness directly from the wave energy resource, the transmission system that is capable of converting fluid-to-mechanical or mechanical-to-mechanical power is a required source to run the generator. There are four types of transmission illustrated in **Error! Reference source not found.**; the hydraulic system, air turbine system, hydro turbine system, and direct mechanical drive system. The rising challenge in the WEC development is that the wave energy always cannot be predicted; create non-uniformed of wave pattern during propagation, always contains different amount of energy and efficiency from time to time. This situation will cause the WEC system create the variable of speed on its generator side. Thus, the conversion system used with this series of generator should have capabilities to cope with these various kinds of speed regulation.

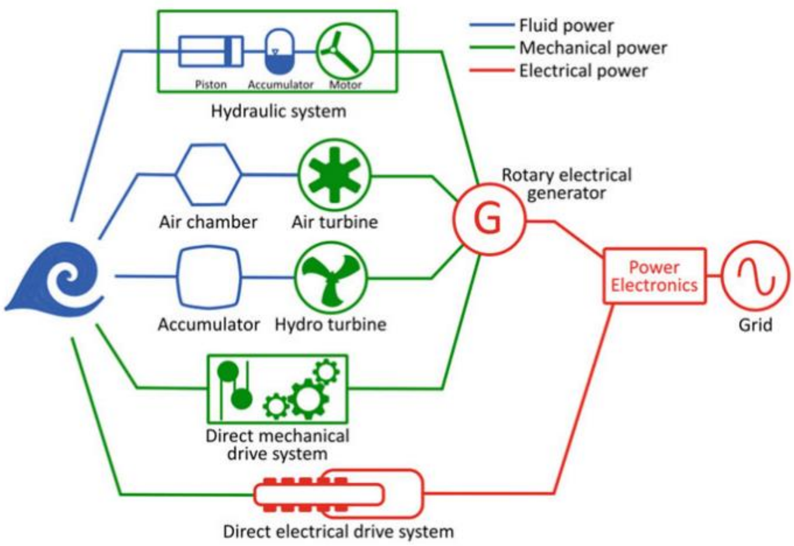


**Fig. 18.** Different paths for WEC system [67]

Basically, the rotary type of generator can be separated into two different categories: variable-speed, which allows the use of power conversion system, and fixed speed, which allows the generator to directly connect to the grid with minimal components integration between them.

### *3.1.1 Variable speed rotary generator*

As previously mentioned, the source of wave energy generates fluctuation in power applied and this will cause the standard generator that uses fixed winding or permanent magnets to deliver variable voltage and variable frequency power. Therefore, due to the frequency requirement of the grid, the variable speed generator cannot simply directly connect to the grid. The intervention of power converters system necessary to integrate with the generator and the grid. There are few generators discovered that use this technique to operate: Doubly-Fed Induction Generator (DFIG), Field Would Synchronous Generator (FWSG) and Permanent Magnet Synchronous Generator (PMSG). Every type has its own advantages and disadvantages. For the synchronous generator type, the variable voltage can be controlled by using automatic voltage regulation for the excitation of the field voltage and for the frequency stabilisation, it requires multi polarity type of generator. Meanwhile, as shown in **Error! Reference source not found.**, for induction generator series, it requires additional hardware controlled system with using capacitor between rectifier and inverter stage to sustain the stable output voltage and its operating speed should be more than synchronous speed in order to establish an operation stage mode.

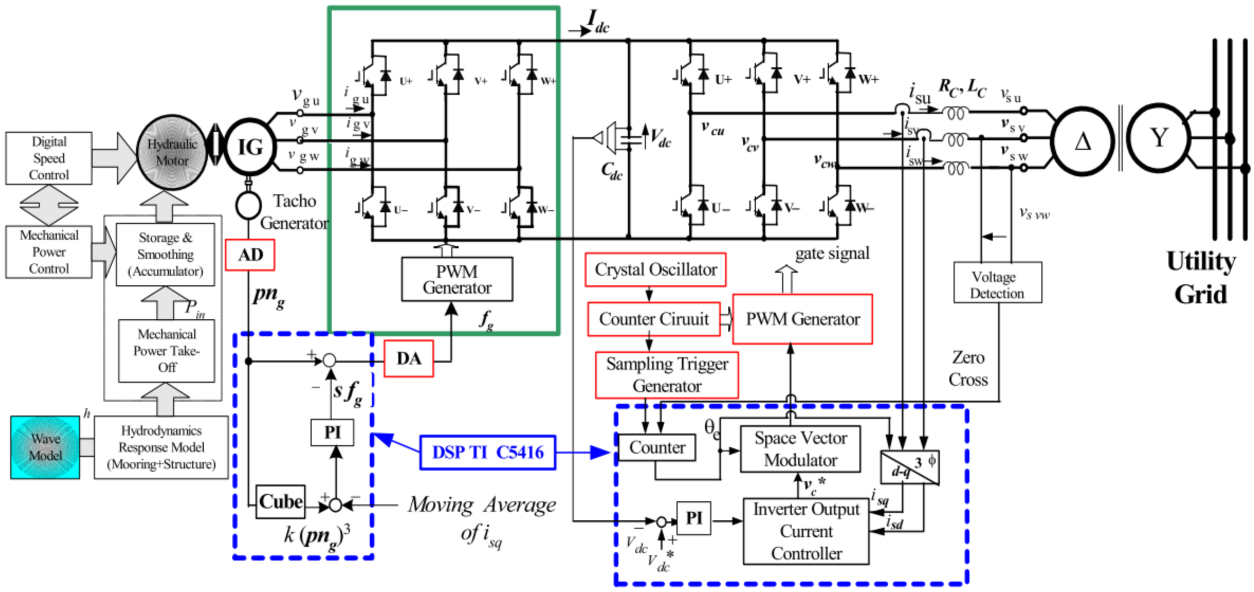


**Fig. 19.** Generalised electrical and power take-off modelling for variable-speed wave energy converter [82]

The advantage of variable-speed electric generators is that the generator can perform either at constant (maximum) torque or constant power [83]. However, during the system at the constant torque and when the generator surpasses the desired frequency, the voltage will no longer able to increase and caused the flux, current and torque to decrease. This phenomenon is known as ’field weakening ‘(flux weakening) and leaves a negative effect due to the constraint of the physical system. To overcome this field weakening effect, it is used as torque control system to power a partial torque load above the rated speed and the control strategy proposed in Pan and Liaw [84]. As the technology progresses, new generator design including the asynchronous or induction singly fed generator, the doubly fed generator, or the brushless wound-rotor doubly fed generator are seeing success in variable speed constant frequency applications.

### *3.1.2 Fixed speed rotary generator*

For fixed speed series generator, it provides less complexity of integration to the grid connection, which avoids the use of expensive power converter and based on reported, it does not add any harmonics into the network [83]. The Squirrel-Cage-Induction-Generator (SCIG) has this fixed speed configuration and most commonly used in renewable energy sector especially in wind turbine. In WEC, this SCIG is successfully implemented in the Pelamis WEC, driven by a variable displacement hydraulic motor [82]. SCIG is simpler than a synchronous generator due to brushless cage construction which are reduced unit cost and ease of maintenance. There is no synchronising need, and performance under short circuit is better than to the synchronous generator [85]. For operation, the system only requires passive capacitor in between grid connection act as local power corrector to stored or released reactive power and to help reduce reactive power drain from the grid terminal. As shown in **Error! Reference source not found.**, this generator configuration requires soft starter system to reduce the inrush current upon initiate the rotation by control the speed and torque only during start-up, providing smooth ramp up performance of rotation to reach full speed. The power corrector unit will help to supply the reactive current to the system during this soft starter operations [86]. Soft starters prevent the generator from damage caused by sudden influxes of power.

Nevertheless, due to the straightforward integration to the grid, there is no complex power electronic system is applied and this will limit the flexibility in implementation of control strategies. Hence, the controllability can only be configured on the transmission stage, which can be either turbine, mechanical or hydraulic transmission.

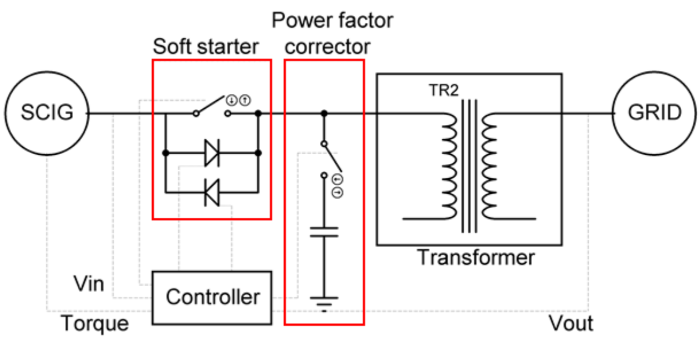


**Fig. 20.** Control system of SCIG, simplify from [82]

### *3.2 Linear Generator*

Linear generator is another type of technology to convert the mechanical power to electrical energy. The working principle is not similar to the rotary type, and it used linear motion strategies to work. At the early stage of research, the linear generator faced a challenge, because the device is too heavy, inefficient, and raising cost to build. By comparing with the rotary type, the power generation will increase when the rotation speed increased due to rapid changing in flux, specifically designed for high-speed rotation. Different case with linear type, it is nearly impossible to harness optimal electricity by providing high linear of motion. It has been reported that in the WEC, it is expected that the linear oscillatory peak of waves is around 2 m/s [87]. Thus, the research on linear technology focuses on a low linear motion to generate the equivalent of power production is keep continuous, the magnet capabilities were identified as the main key to realise this technology into real physical applications.

As the technology progresses, the new magnetic material has been discovered and developed. The power electronics system for converting frequency that uses to generate reliable electrical power from this type of generator with cost-effective of production will make linear generator possible for implementation in actual scale of WEC. The focus lies in permanent magnet devices [81]. The development of high-energy density permanent magnets such as Neodymium–Iron–Boron (Nd–Fe–B), which can produce high magnetomotive force for a relatively small magnet height, has significantly improved the power density of permanent magnet devices [88]. Furthermore, the linear device technologies eliminate the complex interface of the transmission system that happened to the rotary generator technologies. This approach will introduce reliability and maintenance issues, which are important to minimise in offshore environment application [81,89]. Without those intervention systems, the cost, maintenance, and reliability are no longer a major issue. The capability of a linear system to harness direct mechanical power from the source without intermediate loading between them has created great interest among researchers and inventors to develop an advance WEC especially focusing on the WAB category.

The basic working principle of linear generator required two main parts as indicate in **Error! Reference source not found.**, namely, a translator (known as a rotor for rotary generator) and a stator. The translator mounted with the number of permanent magnets that the arrangement follows alternating polarity and usually directly linked to the heaving buoy structure. The continuous linear movement of the buoy will generate magnetic flux caused by the magnetising activity between magnet and windings that installed on the stator part. The stator part acts as the main structure and relatively stationary fixed to the seabed. The magnetic flux later will produce electric current induced from the windings coil in stator.

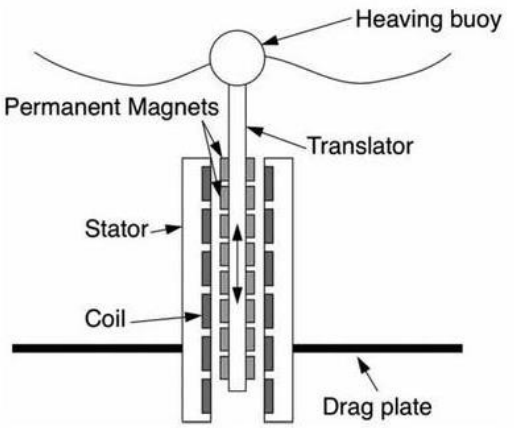


**Fig. 21.** Main components for linear generator in WEC application [90]

There are several topologies of linear electrical generators, including tubular air-cored permanent magnet generator, transverse flux permanent magnet generator, longitudinal flux permanent magnet generator and octagonal linear generator. There is also a proposed new type of topologies linear generator with skewed mounted permanent magnets [91]. The tubular generator type improved the electromagnetic thrust density caused by the force-to-weight ratio, and the implementation proved experimentally by comparing with flat linear topology [92]. For octagonal generator type, it is closer to the desirable cylindrical pattern, that generates more even electromagnetic force (EMF) and capable for power fluctuation suppression [93]. Meanwhile, for transverse device type implemented to the wave energy application tend to produce higher force density, but the disadvantage occurs when the efficiency is reduced to the significant losses with regard to eddy current [94-95].

The major issue in linear technologies is that the production signal is not synchronous to main grid power characteristics in terms of frequency and amplitude signals [88]. The speed of translator continuously changing as the wave propagation is always uneven and varies from time to time. The heave motion that acts to the translator will cause the induced EMF to always vary for both signals. To merge with the grid, these kinds of results pattern should be first rectified and filtered to ensure that fixed sinusoidal frequency and amplitude voltage can establish. The involvement of power electronics is necessary and compulsory for this rectification process to smooth the production signals. The rectification can be either passive or active. For passive filter, the electronics components consist of fundamental diode bridge that generates the power factor of one. The active filter necessary to implement when the power factor generating is not promising after a passive filter is applied. The active filter behaves as resistance and can be arbitrarily of low voltage drop compared with common diode. The electronics device for active filter application can be comprised with the use of active components such as a transistor, thyristors, insulated-gate bipolar transistor (IGBT) or other types of electronic parts.

## 4. Power Electronics Technologies

The power electronics converter (PEC) in the WEC system is required to be fitted in between the harnessing energy from the generator and output load (end user). The research on PE is increased rapidly since the system strategy to supply power production to the on-grid system. PE converters are not studied widely in the early work of the wave energy community, nor mathematical models or physical experiments [13]. At the early stage, mostly the WEC system is in the prototype stage and targeted to supply the energy to the off-grid system either directly connect to the standalone electrical device or others mechanical loading. However, when the fields create more interest to the investor and government to participate, the WEC growth and the fund received enough for large scale development plant. Thus, the targeted productivity of energy increase from a few kilowatts to megawatts capacity.

Without intervention of the PEC system, the high efficiency of energy production is practically challenging to achieve. Thus, this PEC system plays important roles in ensuring that the power generated by the device is in stable condition, providing smooth power oscillation, frequency, and amplitude characteristic meet the on-grid power requirements. The use of the PEC system can practically apply to the rectifier system, storage system, and inverter. In prevalent WEC equipment, there are two common rectifiers in PEC topologies, which namely, active AC-DC rectifier and passive AC-DC rectifier. The strategies are managed by the implementation of the appropriate controller to stabilise and to smooth the power output.

### *4.1 Active AC-DC Rectifier*

The active configuration of AC-DC rectifier with or without combination of DC-AC inverter provide more flexibility in optimising the energy production than the passive approach. Even though it will inject some harmonics to the signals, they can be prevented from flowing through the entire system by preparing a separate low-impedance path for them, which consists of resistor and capacitor, adequately rated and tuned to have equal impedance at the specific harmonics frequency. [96]

highlighted that the energy absorption from the ocean is considered largest when the natural period agrees with the wave period and it means that, there is a possible motion of wave other than the natural one that would absorb more energy. If the WEC system are designed with the appropriate active technique of PEC and precise implementation of control strategies, the more energy absorption could be harvested.

There are several strategies discovered in implementing active AC-DC rectifier to the WEC either in simulation works, laboratory scale or actual physical system. The three-phase full wave rectifier AC-DC with the combination of the DC-voltage source implemented in Tedeschi *et al.,* [97]. [98-101] used an active AC-DC-AC inverter as a part of the PE system to establish the optimum power. The use of the AC-DC-AC converter, includes active or passive strategies during DC stage to tune the optimum power supply to the grid implemented in Igic *et al.*, [102]. Another research [103] used IGBT as a DC buck converter used for smoothing the power input to electrical load bank (battery). Penalba *et al.,* [104] suggested the AC-DC-AC conversion with a back-to-back converter by means of thyristors instead of used common diodes [83]. Many different back-to-back converter configurations based on combinations of diodes and thyristors are considered possible and have been suggested for different applications.

### *4.2 Passive AC-DC Rectifier*

Passive AC-DC rectifier provide less complexity in PEC architecture where only passive components involved for construction including diode and capacitor. The advantages of passive AC-DC rectifier are that it provides cost-effective in development, is easy for fabrication and reduces the cost for maintenance. However, in certain of point it will limit the functionality, where the passive WEC will have natural response that is not optimal [96]. In Thorburn and Leijon [105], the simulation has been carried out by implementing three-phase passive rectifier connected to a five-unit generator with a finite element approach. The supply power was then injected to the DC load. As reported by Rahm *et al.*, the passive diode rectifier was used to convert AC-DC power profile, and during DC stage the capacitor is used to filter the ripple, or unwanted noise [106]. The combination of passive DC-AC inverter is implemented in [97], where the proposed system used AC-DC-AC direct converter with capacitor during DC stage to study the effect on the implementation of control strategies.

Rather than using active or passive AC-DC-AC, O'Sullivan *et al.,* [103] proposed a novel alternative to smooth power oscillation and a fast-response power electronics device with the adaption of distribution static synchronous compensator. Meanwhile, Wang *et al.,* [107] proposed a different approach by implementing high voltage direct current inverter after the AC-DC converter system as a strategy to maximise power to the load.

## 5. The Challenges in WEC Development

Research on ocean energy as future RE sources rapidly progresses either in simulation or in practical experiments. This energy source offers several advantages. Minimal energy dissipation is generated when the waves propagate in large distances, and sea waves provide optimal production in harnessing energy compared with others source [108]. Pelc *et al.,* [109] mentioned that the WECs potentially convert the energy up to 90% of the time, compared with solar and wind harnessing devices, which convert only between 20% and 30%. To fully utilise the advantages of waves energy as abovementioned, the challenge rises on the technical aspect in term of maximising the performance of WEC and hence be able to face commercial market and be competitiveness in the global energy sector.

The first challenge is designing conversion system of WEC that can exploit wave motion which are considered slow, erratic, and often change over time. Then, ideas are needed to turn this complicated wave motion process into useful rotational of motion to excite the generator. Finally, the production processing of electrical output should be carefully calibrated to allow integration with the standard on-grid electrical network in terms of its frequency, harmonics, and amplitude response. The fluctuation of wave propagation will generate various respective power production, and it would ruin the existing on-grid system if this device failed to cope up with the standard specification of power from the utility network. As mentioned in section 4, the implementation of PE technologies is compulsory in providing smooth electrical power output.

Next, the development of the WEC located offshore is more challenging than near shore. Even though the wave power energy at the offshore site quite promising, the wave direction is highly variable. The design of the device should have the capability to self-align accordingly to face the incoming wave to harness the energy optimally. The directions of waves near shore can be largely determined in advance, owing to the natural phenomena of refraction and reflection [88]. In short, the variable and irregular waves motion present crucial impact in designing the device. All necessary components including mechanical or electrical equipment should be rated accordingly to the wave strength at the deploy location to ensure that the device operates efficiently and can withstand with the extreme environment although it happened rarely. This aspect, for sure, creates an engineering challenge and most importantly raising the capital cost for the device construction process.

Based on the reviews, the comprehensive study on WAB device technologies has been carried out and this paper, concludes that the recent development of the WECs is more focusing on floating type technologies specifically in ET category. The main factor is investigated which influence this selection, including the development process of floating type WEC requires less complexity in designing and fabrication aspects compared with submerged type. When the WEC is designed submerged, the structure of the device should be capable of coping with up the harsh weather condition, robust to wave regime and able to withstand in an extremely high-pressure environment. Under the sea level, the pressure is high and keeps on increasing when going deep.

Thus, the structure of the device should have a better mechanical sealing protection system to prevent the water from penetrating the compartment area where the crucial electrical items, including generator, and all electronic components placed. Indirectly, it could spike the development cost process and also increase the maintenance rate for long-term use, as regular access to the WEC underwater is much more expensive compared to the WEC float. Nevertheless, for a floating device, there are also design challenges to mitigate the highly corrosive environment of devices operating at the water surface [108]. In addition, the positive effect of float on WEC is capable of producing optimum results in controlling the wave regime in the form of heave and surge (back and forth) as translated into the output of electrical power as shown in Table 2. For future energy generation plant in farm scale, the floating device looks more relevant, and provides less complexity of integration between each device. The Pelamis WEC technologies that have already been deployed in multi-unit arrangements have proven this, and the electrical power generated is already integrated into the national on-grid network [47]. The floating WEC that installed offshore site also provides a minimal effect on environmental issue and have the lowest potential impact in term of interrupting the marine ecosystem on the seabed including reefs and that are the natural habitats for marine life [88]. The estimation of the life cycle emission caused by the typical energy device installed near shore was discussed in detail in Thorpe [11].

For the generator types, the use of rotary generator proved to be a decent decision in generating electricity, widely used in the hydroelectric-turbine and wind-turbine application. However, the intervention of the converter system is still required to link with the generator, converting from the waves heave or surge motion for rotation of generator shaft and thus resulting in an escalation of the cost. O'Sullivan *et al.,* [87] discussed the suitability of those type generator to suit in WEC. Several considerations have been made from his works, in terms of cost factors, environmental impact, electrical efficiency, and the technical results that have been carried out with the approach of computational simulations. The obtained results show that the synchronous generator type is the preferred option with few advantages including; better energy yield, weight, and controllability, despite the requirement for a full frequency converter between the generator and the grid [88]. Meanwhile, the DFIG is said to be an alternative option to consider since the construction system consists of a brushed type and is driven by a gearbox system, which requires cost in maintenance.

The linear generator type provides simple methods since the system only required a linear translation of motion to operate and can directly follow the motion of the waves by directly tethered to the buoy. Nevertheless, the technology for this type of generator is still in the research and development stage, which capable to provide the optimal output of electricity merely doubted. Also, most WEC on the reviews show that this linear generator type installed is submerged on the seabed and thus requires the most robust mechanical structure to work continuously under extreme pressure below the sea level. In addition, its routine system maintenance is necessary to prevent leakage, which can harm the marine environment in the event of leakage [110].

## 6. Conclusion

This paper has categorized the WAB working principle into two groups with regard to the installation either submerged or floating.  Different design of WECs with their working principle including PTO system and the ability of electrical power generation are explained. As indicated by this paper, although many research and developer have been performed on laboratory scale and real-scale test of WEC, the WEC community including researchers, engineers and inventors would benefit a lot from more comparative studies and give them some ideas for the next generation of WEC studies or development. Some technologies benefit from the long operating periods, e.g. Pelamis, where different generations and improvements have been made and rapidly tested in the real sea environment, while other technologies, including WEC, are still being tested on a laboratory scale, await experiences from experiments in the sea condition.

The authors suggest that the floating type of WEC as shown in Table 6 should be used as a starting point for future comparative studies as it receives more attention and offers more positive advantages than submerged categories, especially in terms of requiring minimal financial and development costs. Another factor, wave regime on the ocean level is quite promising especially at the offshore site and this type of WEC really suitable for working on this harsh environment. Even though the construction of the device needs to face the difficulty in the engineering design procedure, but it is not much compared with the device install submerged where the challenge is significantly rising.

Additionally, in the near future more focus will be paid on working on linear generators. While stability and robustness can still be achieved in linear generator technologies compared with the already mature and proven rotary generator, as stated in subsection 3.2 this type of generator still has great potential and positive impact. Where it is possible to remove the complicated configuration of the transmission system that occurred when using the rotary generator, which would help them enhance the currently available WEC design and minimise the development cost. Furthermore, the invention of permanent high-energy density magnets will help the WEC harness the wave energy optimally and transform it to usable electrical energy with minimal losses.

Recently, the WEC technology are not widely commercialised and are neither mature for global implementation. Although there are various devices invented and developed with the approach of WAB techniques, the vast majority of them are still in the prototype and development stages. Therefore, it is too early to announce which of these available technology devices can potentially become the most prevalent one to be commercialised in the near future. There are many hurdles and significant obstacles to realizing the WEC for commercialisation and keeping it reliable and stable, including the high capital cost of WECs for production processes calculated by electrical power generation costs, maintenance costs and the adverse working weather conditions that these devices have to cope up with, requiring additional safety features that could gradually raise the capital cost.

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