

Wave Energy Converter

Subjects: [Energy & Fuels](#)

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The overview of the types of wave energy converters (WECs) are classified through operational principle, absorbing wave direction, location, and power take-off.

[ocean wave energy](#)

[wave energy converter](#)

1. Introduction

The sea surface waves provide a large amount of green energy and could make an enormous difference to global energy demands going toward the sustainable world. One of the factors that makes waves desirable for harvest is that they have tremendous power density compared to many renewable energy sources ^[1]. Wave energy seems to have the second-highest potential of all ocean clean energy sources ^{[2][3]}. The theoretical potential of wave energy is shown in Table 1. Wave energy sources have been evaluated at global ^{[4][5][6]} and regional ^{[7][8][9][10]} levels and the volume of wave energy available is high enough to stimulate significant interest in exploitation. The estimated worldwide demand in 2014 for electrical energy reached 19,800 TWh/year ^[11] with a worldwide wave energy reserve of the same extent ^[12]. However, estimates of theoretically usable wave energy capacity on a worldwide scale are widely recorded between 2000 and 4000 TWh/year ^[13]. Environmental problems, including air pollution, global warming, and severe weather, due to colossal fossil oil use are gradually being discussed. For electricity generation in 2040, fossil fuels are expected to account for greater than 35% of the total energy consumption ^[14]. In this sense, it is much more essential to harness renewable energy sources such as wind, solar, and ocean wave energy.

China, America, India, and European countries are on the frontline of establishing strategies for incorporating the wave energy of the ocean into their systems ^[15]. Government agencies within these countries funded studies to carry out resource assessments ^[16] and provided test sites and laboratories for the development and planning of energy conversion systems ^{[17][18][19]}. Apart from state-funded studies, some studies are conducted by universities ^[20], private organizations ^[21], research centers ^[22], and individuals who are all involved in an attempt to promote ocean energy into the public consciousness of a renewable energy sector. Due to the immense potential of wave energy ^[1], a wide range of wave energy converter (WEC) ideas has been formed to capture energy from waves. It is noted that now there are more than 1000 WEC prototypes ^{[23][24]}. Different studies have identified challenges resulting from the volatility of the properties of ocean waves and the sustainability of energy converters of the waves in a severe ocean environment ^[25].

The stability of the wave energy converter requires a mooring system. Present mooring systems and design specifications cannot completely fulfill the demands of the offshore WECs. It is according to the four properties of the wave energy converters which place them apart from the other offshore installations: function, operation, investment/revenue relationship, and the consequences in the event of failure. In the case of offshore WECs, the failures of a mooring system seem to be minor compared to offshore platforms. As such, strict safety requirements are not required. However, recommended offshore standards are needed for the implementation, and this results in the total investment between 18% [26] to 30% [27] in mooring systems. To optimize the energy efficiency of the wave energy converters, they need to be deployed to high-energy zones. Those are areas where the wave condition is high and, as a result, where a converter and also its mooring mechanism would be under extreme loading. Some of the WEC types are motion-dependent that require oscillations in waves, mostly in resonance, to obtain energy. Such oscillations will cause a mooring system to make high amplitude motions at a high frequency, causing higher dynamic tensions in mooring lines, mainly when it is in resonance. The performance of the motion-dependent devices is affected by the mooring system, because as mooring lines adding their mass (added mass), damping, and stiffness it changes the dynamic responses of WECs. The mooring system mass and stiffness are not detrimental and may also increase the performance of the converter, as stated in reference [28]. In addition, the additional mooring damping, contributing to the stabilization of floating structures [29], dissipates energy that may be exploited by WECs that are motion dependent.

An excellent mooring system for floating WECs will consider not only the possible consequences of the power take-off and device motions and but also ensure stability, be easy to maintain and monitor, and reduce installation and material costs. In this paper, the overview of the types of WECs and their mooring configurations, components, requirements, modeling approach, design consideration, suitable software, and challenges are discussed.

Table 1. Global resources of wave energy [30].

World Regions	Wave Energy Potential (TWh/y)
Asia	6200
New Zealand, the Pacific Islands, and Australia	5600
South America	4600
North America and Greenland	4000

Africa	3500
Western and Northern Europe	2800
Central America	1500
The Mediterranean Sea and Atlantic Archipelagos	1300
Total	29,500

2. WECs

The conversion of wave energy into useful energy, such as electricity, is performed through WECs.

2.1. Historical Background

The prospect of conversion of wave energy to useful energy has encouraged various inventors: by 1980, more than 1000 patents were already registered [31] and since then, the number had risen considerably. In 1799, Girard filed the earliest best known such patent in France [32]. By the late-twentieth century, several patents relating to the conversion of wave energy were in existence [33]. Former Japanese naval chief Yoshio Masuda can be called the founder of advanced wave energy development. He developed a navigation buoy equipped with a wave-driven air turbine. Such buoys are the components of the oscillating water column (OWC) [34]. The revival of wave energy work within the 1970s–1980s was mainly a result of oil crises in 1973, and the crises generated recognition of the spatial and temporal importance of the reserves of fossil fuel to policymakers and governments [35][36]. Governments [37][38] and intergovernmental associations, thus, spearheaded several developments and research activities. The 1973 oil crisis sparked a significant shift in the scenario of renewable energies and increased interest in wave energy generation on a full scale. In 1974, Stephen Salter introduced wave energy to the community of researchers and had become a landmark [39].

Several articles on the conversion of wave energy were written as books, journal papers, reports, and conference papers, such as McCormick's pioneering book [31], released in 1981, and the books of Shaw [40], Justus and Charlier [41] (finished wave energy long chapter in 1986), Cruz [42], Ross [32], and Brooke [43]. In 1999, a report prepared by the Energy Department of the UK [2] and final report on wave energy (2003) [44] from the Thematic Network of European (European-Commission-funded project) provide a wide variety of data. Shorter reviews are available [45][46][47].

2.2. Wave Energy Converter Classifications

To date, numerous different methods have been developed to convert the wave energy to electrical energy. Around 53 different technologies of wave energy were reported in reference [48] in 2006. Typically, they are classified as per conversion type. The classifications of WECs are more in detail in references [49][50][51].

2.2.1. Operational Principle

The operating principle describes how the wave energy converter interacts and absorbs energy from incoming waves. Falcão has proposed classification by operating principle [52].

Oscillating water column (OWC): The OWC is a floating hollow or fixed device that compresses and decompresses compressed air using the change in wave induced in the water level within the chamber [53], as shown in Figure 1. The pressure difference in the chamber forces air to move via a turbine that is coupled with the generator. If built near the shore, OWCs will act like breakwater structures to secure the coastline [54]. Some OWC devices have a natural installation advantage when installed close to the shore. Some examples are Energetech [55], OceanLinx [56], WaveGen Limpet [57], Yongsoo Power Plant [53], and Pico OWC [58]. Some examples of floating OWCs include Mighty Whale [59], the Spar Buoy [60], and Backward Bent Duct Buoy [61].

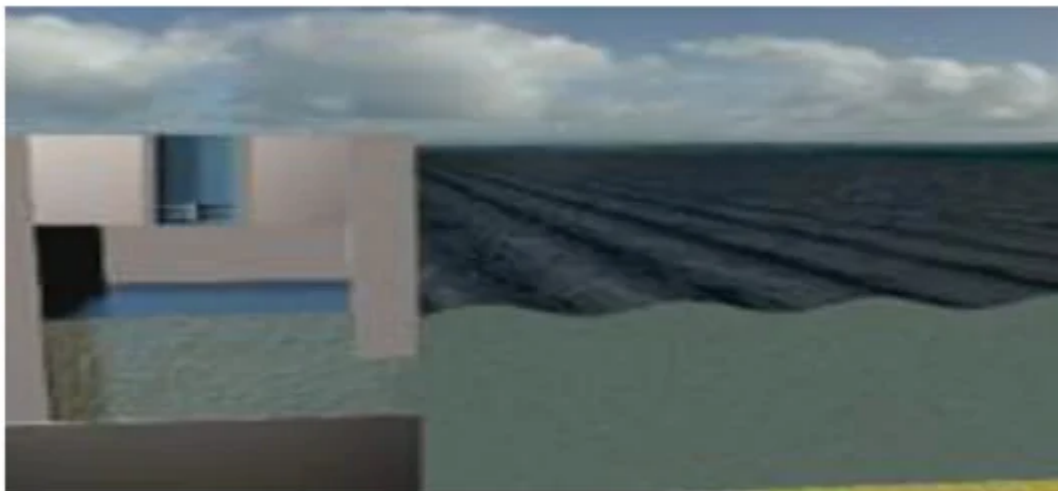


Figure 1. Oscillating water column [62].

Oscillating bodies: Oscillating body is a generic term used to identify WECs that derive power from wave-induced oscillations of submerged or floating structures primarily in surge or heave.

Heaving type devices are commonly constructed as axisymmetric buoys just below or on the surface of the water, extracting power from the wave's vertical motion. A total of 74 listed companies of wave energy by the Marine Energy Centre in Europe [63] concentrate on the production of heaving type point absorbers. These include Cor Power WEC (floating WEC of bottom-referenced connected to pneu-mechanical drive) [64], Power Buoy [65] (floating system of two-body self-referenced with hydraulic power take-off (PTO), as shown in Figure 2), the CETO

system [66] (submerged converter of bottom-referenced with hydraulic PTO), and Sea-based wave energy converter [67] (floating system of bottom-referenced coupled with linear generator).



Figure 2. Power buoy [65].

Oscillating wave surge (OWSC) converters are made up of the flapping structure, for example, as a plate, hinged on the seafloor or submerged reference base, as shown in Figure 3. There are currently 14 different oscillating wave surge converters developed around the world [63], including BioWare, Langlee, and Oyster. The (OWSC) power output is lower compared to bottom-fixed because the reference base that is built to be stable always tends to pass in waves and often does not have an appropriately high reaction point of impedance [68].

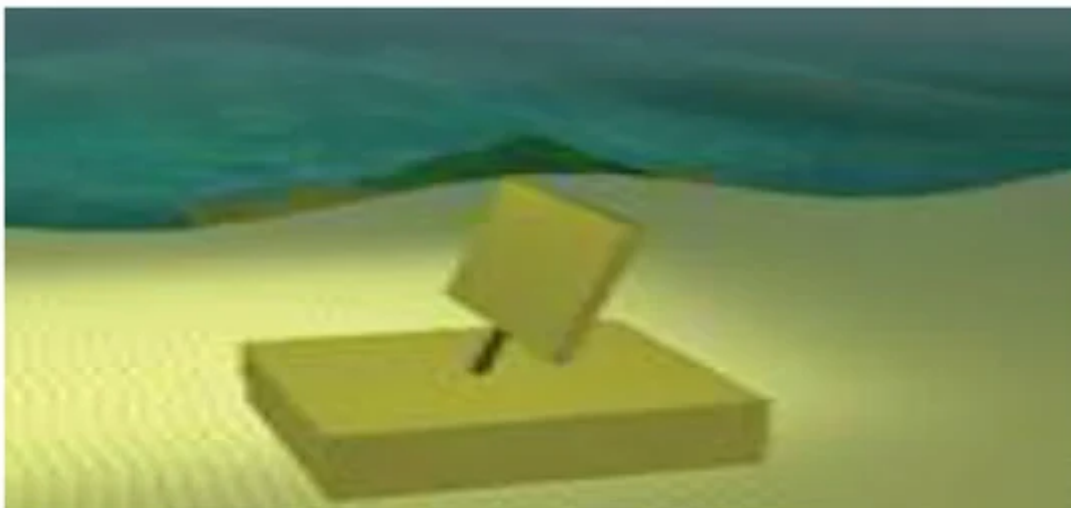


Figure 3. Oscillating wave surge converter concept [62].

Submerged pressure differential: In general, this device's position is near the shore and anchored to a seabed [62]. They usually are submerged point absorbers fixed and located near shore [69] and are Comprised of one or more chambers that are air-filled in which the pressure fluctuates based on the incident wave phase (trough or crest).

The changing pressure in the presence of deformable chambers results in a continuous airflow within the device, which is converted by air turbine into electricity. This concept is found in the Bombora WEC [70]. The air chamber for rigid structures consists of one constant and one rotating component where there is a variation for chamber volume due to the changing pressure. The moving component down and up motions transform into electricity by the linear generator; it is applied in Archimedes Wave Swing [71], as shown in Figure 4.



Figure 4. Archimedes Wave Swing [62].

Overtopping: The overtopping mechanism consists of a water reservoir above the surface level of the ocean, which causes the water of the reservoir to transfer to the sea through the turbine structure. The overtopping earliest devices in Norway are the wave power tapered channel devices (Tapchan) [72]. They have a 350kW nominal power. Wave Dragon is another conventional device and is a floating device designed in Denmark [73], as shown in Figure 5. The design of the slope Seawave Cone Generator [74] is similar to the Wave Dragon. Wave Dragon is a universal application that uses as overtopping devices, and the Wave Dragon structure is shown in references [73][75]. Wave Dragon is a multiple MW plant of production with maximum power take-off performance and fast maintenance. Moreover, because of its large size, it is costly. Wave Dragon covers a vast region of the ocean and has an environmental impact.



Figure 5. Wave Dragon [73].

Since these WECs have substantially different performances, the estimated hydrodynamic efficiency is shown in Table 2, and WECs’ breakdown by the principle of operation is shown in Figure 6.

Table 2. Different wave energy converters’ (WECs’) efficiencies [76][77].

WEC Device Type	Efficiency %
Pressure differential	38
Oscillating water column (OWC)	29
Overtopping	17
Oscillating body—Heaving	16
Oscillating body—Surging	37

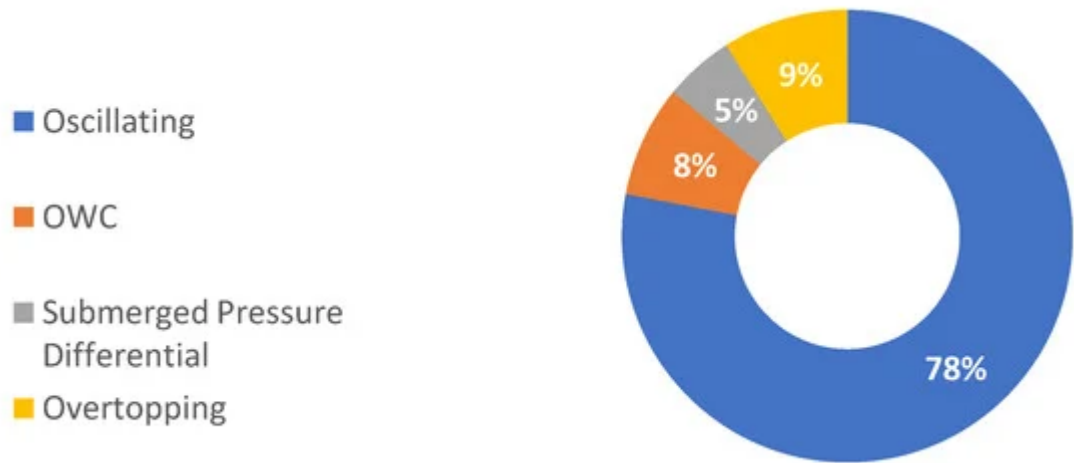


Figure 6. WECs, based on the operational principle [78].

2.2.2. Direction

The WECs, according to the wave propagation direction, are classified as follows:

Attenuator: Usually, the attenuator is a flexing device, mounted parallel with the direction of propagation of the wave. An attenuator works by absorbing the energy from their two arms' relative motion when the wave moves through them. This device is also a floating-type device that acts in parallel with the path of the wave and drives the waves efficiently [62]. The Pelamis [79] is a typical example. Three Pelamis units formed the commercial world's first wave-farm of Portugal's coast in September 2008 [80], as shown in Figure 7.



Figure 7. Pelamis wave farm [81].

Terminator: This device intercepts waves by standing perpendicular to a prevailing direction of the wave [82][83]. The device Salter's Duck, invented by Dr. Stephen Salter at Edinburgh University in 1978, is probably the most known of this kind, as shown in Figure 8.



Figure 8. Salter's Duck [65].

Point absorber: Point absorber has considerably smaller dimensions than a wavelength and can produce power independently of the direction of the wave propagation. The buoy can oscillate to one degree of freedom or more, as shown in Figure 9. A motion of the buoy damping extracts energy, and a generator converts it into electricity. A pitching type point absorber is the example of the Salter's Duck [39]. Wave Star [84], FO3 [85], and Manchester Bobber [86] are heaving type multipoint absorber devices.

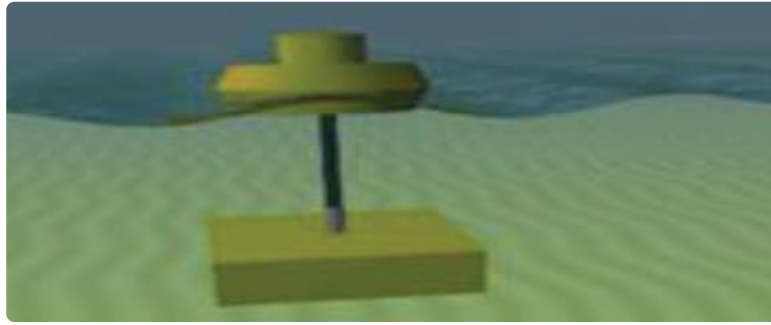


Figure 9. Point absorber [\[62\]](#).

Quasi-point absorber: Presented by Hals and Falnes [\[87\]](#), quasi-point absorbers characterize axisymmetric WECs, which are unresponsive to the direction of wave (like point absorbers) but have fairly broad dimensions comparable to wavelengths (like terminators).

A summary of WECs based on orientation is shown in Figure 10.

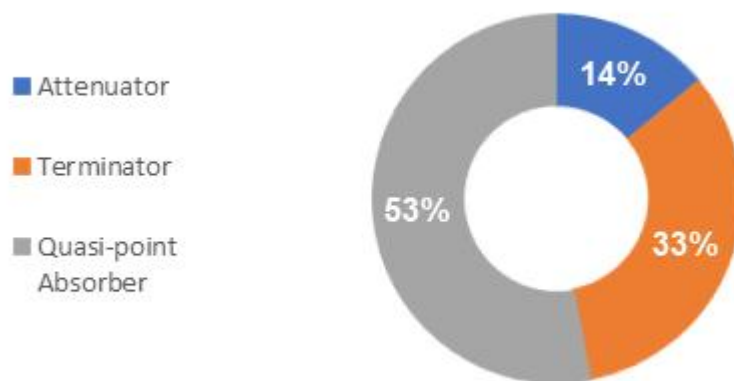


Figure 10. WECs based on orientation [\[78\]](#).

2.2.3. Location

Wave energy converters are classified based on the location as offshore, nearshore, and onshore.

Offshore locations: A higher energy level of waves in deep water makes the offshore devices more impressive for the production of wave power [\[83\]](#). Offshore devices, due to the severe climatic conditions, can sustain larger loads; however, they are much more challenging to deploy and operate.

Nearshore: These devices are referred significantly to as lower water in which converters are attached commonly to an ocean floor. The example of a nearshore type device is WaveRoller [\[88\]](#).

Onshore: Onshore devices are fixed on the shoreline, with the benefit of being easy to maintain and install. Furthermore, moorings of deep water are not required, and the risk of storm damage to onshore devices is minimal, but the wave regime is less efficient.

A summary of WECs based on location is shown in Figure 11.

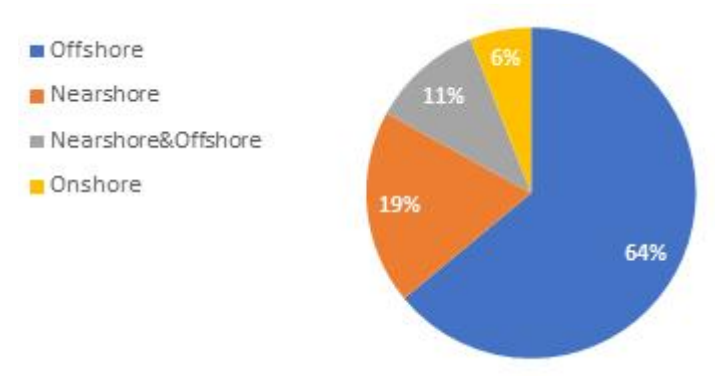


Figure 11. WECs based on location [78].

2.2.4. Power Take-off

Typically, recognized power take-off (PTO) is the process where energy passed between the WEC and the waves, directly or subsequently, turns into a usable form [89]. The types of PTO include hydraulic, hydro, pneumatic, and direct-drive, and their efficiencies are shown in Table 3. The critical challenge of the development of PTO is that the machines must work at lower speeds and higher forces, whereas typical electrical generators are planned for low torque and higher speed motion. Although the efficiency of the hydraulic system is relatively low (see Table 3), it is most suitable for extracting wave energy, as seen in Figure 12 and further WEC examples with their (PTO) systems presented in Table 4.

Advancements and improvements continued in the wave energy sector, and a detailed assessment of power take-off is provided in reference [90].

Table 3. Power take-off (PTO) systems' efficiencies [91].

WEC Device Type	Efficiency %
Hydro	85
Pneumatic	55
Hydraulic	65

Direct mechanical drive	90
Direct electrical drive	95

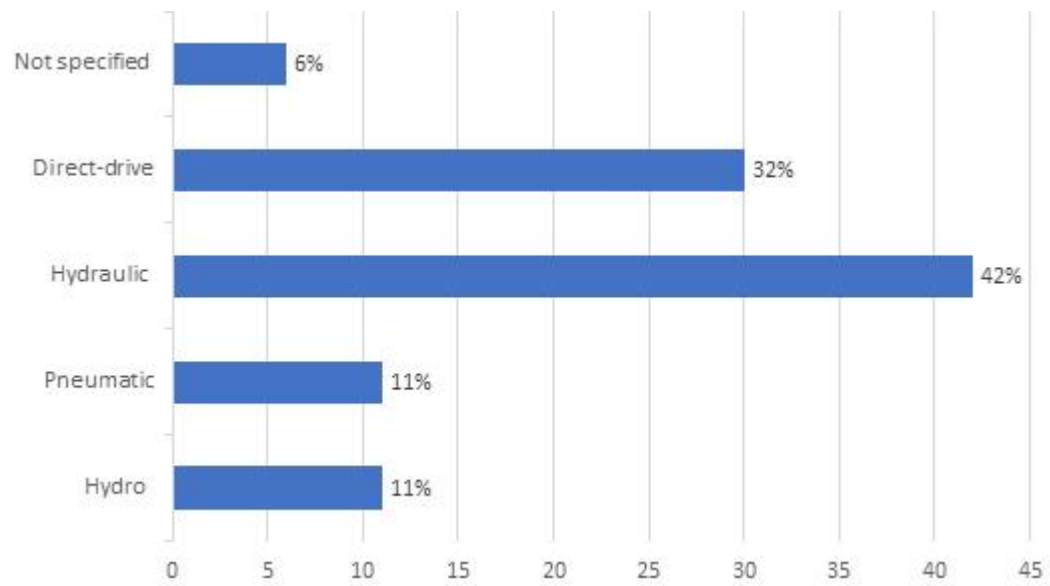


Figure 12. WECs based on PTO principle [78].

Table 4. WEC examples with their (PTO) system.

Name of WEC	Type of WEC	PTO	References
Pelamis	Pitching system	Hydraulic system	[92]
Wavebob	Heaving body	Hydraulic system	[93]
SEAREV	Pitching system	Hydraulic system	[94]
REWEC3	OWC	Wells turbine	[95]
Sakata	OWC	Wells turbine	[96]

AquaBuoy

Heaving body

Impulse turbine

[\[97\]](#)

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