Advancements of Wave Energy Converters Based on Power Take Off (PTO) Systems: A Review

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Abstract

Ocean waves contain one of the world's largest untapped and predictable renewable energy sources that can be used to fulfil the energy demand in the present energy crises situation. There are many devices that have been proposed and prototyped in different countries all around the world to harness wave energy based on different power take-off (PTO) systems. The aim of this article is to review the power take-off (PTO) systems of the wave energy converters (WEC). The review starts with a brief introduction and background of wave energy. Following this, a novel classification of WEC systems is introduced. Then, the WECs based on the different working methods of their power take off systems are briefly reviewed. This includes an analysis and comparison of advantages and challenges of the power take off systems. Aspects of current international research and development activities and networks for wave energy is also discussed. The current market of wave energy technologies is also assessed, showing that the mechanical direct drive system is the most popular. Hybrid PTO systems are seen as an important development for the future.

Key Words: Ocean waves, Power Take off system, wave energy converter, working methods, performance

1. Introduction

To solve the present energy crisis and pollution problems, wave energy can play an important role because of its energy density and availability. To harness energy from ocean waves there are many research works proceeding all over the world. Research on wave energy technology started informally in the 1940s by Yoshio Masuda, a Japanese marine captain, who invented a navigation buoy based air turbine PTO system which was later named as the (floating) oscillating-water-column (OWC) (Antonio, 2010; Falcão and Henriques, 2016). Academically the research started in the 1970s when the fossil oil price increased and the Middle East restricted oil supply (Polinder and Scuotto, 2005). By the 1980s, the wave energy research slowly stopped because the price of oil again reduced and the necessary funds to continue research in this field was not available. Some researchers from Europe, especially from UK and Norway did the majority of the early work and during this time the researchers mostly focused on hydrodynamic systems and developed the point absorber type of wave energy converters and the oscillating water column type of device concepts and the fundamental theoretical understanding of ocean wave energy (Elwood et al., 2010; McArthur and Brekken, 2010). It was then several decades before the research of wave energy started again, driven by increasing energy demand, the price of conventional energy, and pollution and climate change concerns. Therefore, the academic research into ocean wave energy can be divided into two phases as in the late 1970s and at present. Up to date there are many wave energy converters (WEC) that have been developed and deployed in different countries and several hundred WEC projects around the world are still at various stages of developments. This number is continuously increasing as new concepts and technologies are developed. Day et al (Day et al., 2015) summarised that since 2015, worldwide there are more than a hundred projects and more than one thousand patents that have been developed in Europe, USA, Japan, China and Asia. Different concepts, techniques, designs and working principles have been investigated using the WEC to harness energy from the ocean waves, therefore the classification of WEC depends on different aspects. Wave energy systems can be classified by different methods such as according to location, structure, working or operational principle, size and orientation, and power take-off systems (Antonio, 2010; Czech and Bauer, 2012; Falnes, 2007; Hong et al., 2014; Wang et al., 2018). The most well-known diagram of the WEC classification was presented by Falcão et al (Antonio, 2010). Based on installation location, the WECs can be classified by three types: (1) Onshore devices which are usually designed to be installed at or to the shoreline; (2) Offshore devices that are installed in deep water (>40 m); (3) Near shore devices which are deployed in shallow water regions (water at depths less than 20m). Moreover, some new PTO technologies have recently been added to the WEC classification. The working principles of the PTO system with their classification, as developed in this paper, are shown in Figure 1.

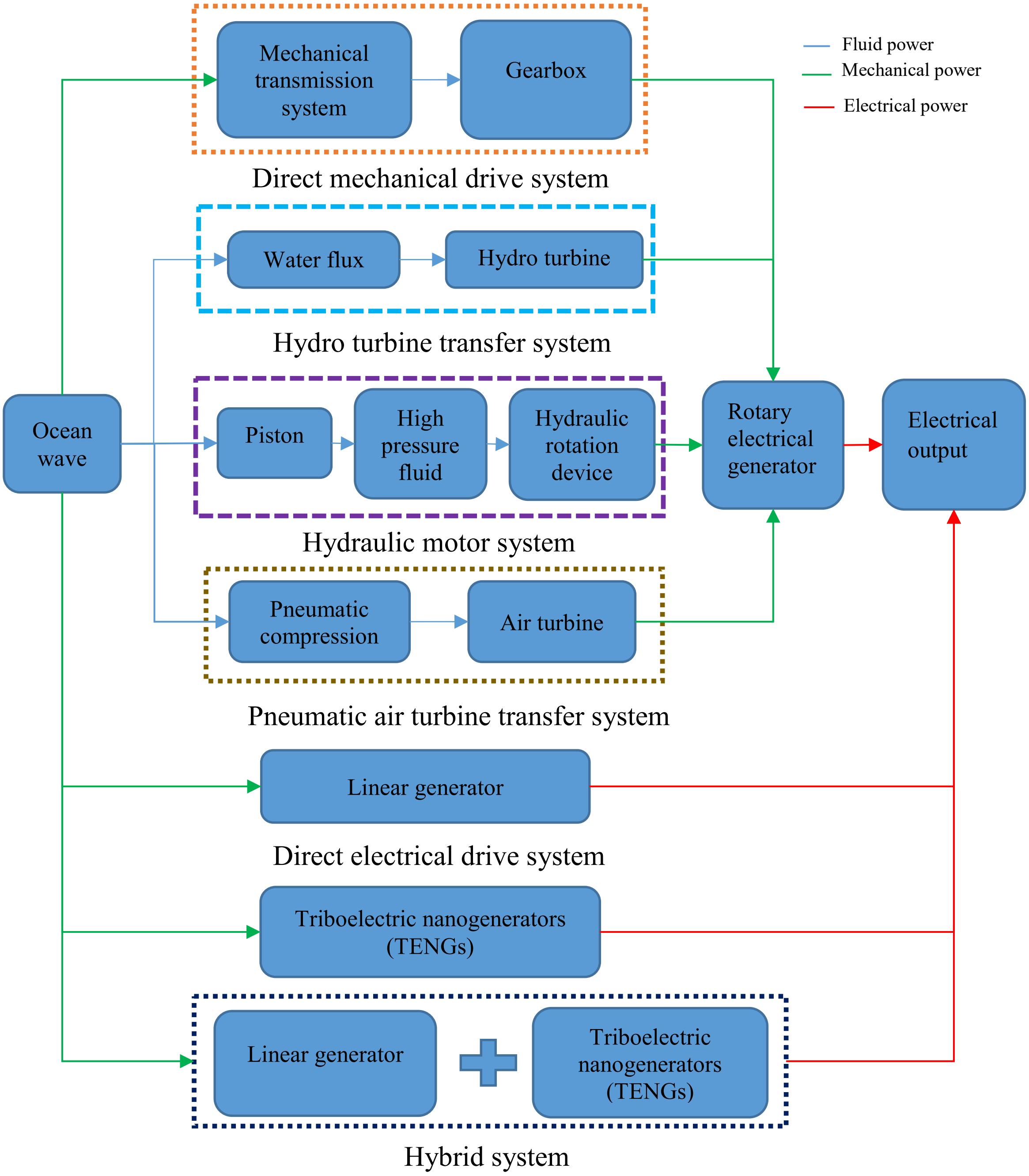

Figure 1: The working principles of the PTO system

The current status, development and future perspectives of ocean wave energy of different countries like US, China, Europe etc. can be seen in (Clément et al., 2002; Cruz, 2007; Kofoed et al., 2006; Lehmann et al., 2017; Magagna and Uihlein, 2015; Zhang et al., 2009). Emre Ozkop and Ismail H. Altas (Ozkop and Altas, 2017) listed almost all publications in the literature based on WEC classifications, research projects, control systems, validation and generator types which have been published up to 2017. Falcao et al (Antonio, 2010) and Johannes Falnes (Falnes, 2007) also presented excellent review articles of wave energy technologies. There are also some books that have been published by T W Thorpe (Thorpe, 1999), Johannes Falnes (Falnes, 2002), Cruz (Cruz, 2007) and others (McCormick, 2013; Pecher and Kofoed, 2017).

Power take off (PTO) systems are at the heart of wave energy converters (WEC) and many academic researchers from several universities and many wave energy technology developer companies are actively working to develop and improve the PTO system (Babarit, 2013; Babarit and Clément, 2006; Babarit et al., 2009; Clément and Babarit, 2012; Cretel et al., 2011; Folley et al., 2012; Folley and Whittaker, 2009; Fusco and Ringwood, 2012; Hals et al., 2002; Saulnier et al., 2011). So far there are many concepts that have been used in PTO systems to harness maximum energy with low installation and maintenance costs, as can be seen in Figure 1. Previously published review articles have focused either on the challenges, current status, and development of WECs or classifications based on working principles and generators, with a brief discussion on the various parts of the WEC and energy harvesting systems. However, there does not appear to have been a single article that presents the review of WECs based on the power take off (PTO) system. It is known that the economic viability, efficiency and complexity of the structure of the WEC depends on its power take off (PTO) system. Therefore, with the aim to find the success of research, advancement and deployment of power take-off (PTO) systems of the WEC, a comprehensive study is required where all past and present works are reviewed. It is anticipated that this present review work can offer novel insights into the range of PTO systems that are being used for WECs with the intention of encouraging new research activity in the wave energy field.

2. Wave energy converters based on Power Take off (PTO) systems

There are many researches works that have been done to develop the PTO system of the WEC, using various concepts. Among all the working methods of the PTO systems, the hydraulic motor, turbine transfer and direct mechanical and electrical drive based working methods are the very well-known and the most used methods. However, there are some new techniques such as the triboelectric nanogenerator, hybrid systems and others that have been used in the last couple of years to develop the WEC PTO system. This section will review and discuss the PTO working techniques with their design methods and research work.

2.1 Hydraulic motor system

Hydraulic motor-based PTO systems are one of the well-known methods which can be used for wave energy conversion in WECs to convert the low-speed oscillating motion into energy (Drew et al., 2009). The hydraulic motor-based PTO system is the most suitable device for generating usable electricity from wave energy, particularly for the wave-activated-bodies wave energy conversion system. Thus, the hydraulic motor can utilize both translation and rotational types of wave energy conversion systems (Jusoh et al., 2019). Jose F. Gaspar et al (Gaspar et al., 2016) summarized the mathematical and numerical models of the hydraulic PTO concept which can be implemented for different types of WECs with reliable, standardized and scalable technology.

Hydraulic types of PTO systems generally consist of a hydraulic cylinder or ram, hydraulic motor, accumulator and generator. The schematic diagram of a typical hydraulic motor type PTO system is shown in Figure 2. Normally the ocean waves drive the hydraulic ram to increase the pressure of a working medium, (usually hydraulic oil) meaning that the hydraulic cylinder of the PTO system converts the translation or rotational motion into hydraulic energy which runs the hydraulic motor. The hydraulic motor then drives the generator to generate energy (Drew et al., 2009; Zhang et al., 2012). The working principle of the hydraulic systems have been described in (Gaspar et al., 2016; Henderson, 2006; Lasa et al., 2012). The control of the PTO force is also the major factor to increase the efficiency of the WEC and there are many control systems such as Declutching control and Latching control that have been proposed by researchers (Babarit et al., 2009; Xie and Zuo, 2013). The characteristics of hydraulic PTO systems are very favourable for WEC therefore there are many WECs that have been proposed and designed using this approach (Blake and Chaplin, 1998; Henderson, 2006; Salter, 1979). For increasing the efficiency of the WECs there are many research works that have been done to improve the designs of the hydraulic pump or motor and control systems (Budal and Falnes, 1977; Eidsmoen, 1998; Falcão, 2000; French, 1979; Heath et al., 2000; Salter and Rampen, 1993).

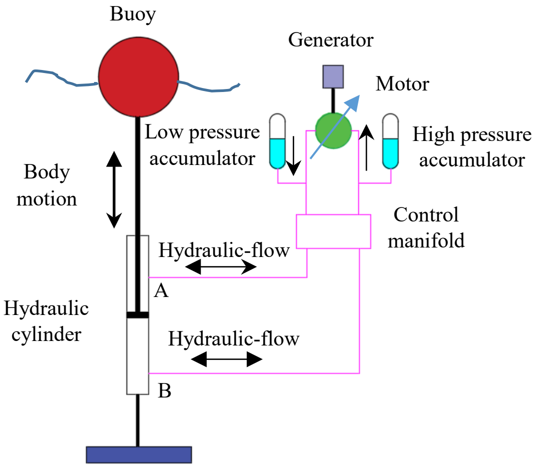

Figure 2: Typical hydraulic motor based PTO system (López et al., 2013).

Among the hydraulic PTO based WEC, the Pelamis (Yemm et al., 2012), Duck (Cruz and Salter, 2006) and Wave Roller (WAVEROLLER, 2018) designs were some of the first to be developed and are very well-known (Lin et al., 2015b). The Scottish Pelamis Wave Power Company developed the Pelamis WEC and installed it in offshore from Orkney, Scotland for harnessing 750 kW of power by using the surface wave motion (Hagerman, 2004). The working method of the Pelamis has been discussed in Ref. (Hagerman, 2004). AW-Energy Ltd developed a series of Wave Rollers and deployed them in Portugal for testing the performances during two different years, 2007 and 2012 (Lin et al., 2015b; Lucas et al., 2012), as shown in Figure 3. The rated power of these two devices were 100 and 300 kW, respectively. Professor Salter at the University of Edinburgh proposed a WEC in 1974 which was known as the Duck (Salter, 1974). The Duck as shown in Figure 4 has been designed in such a way that the buoy travels with a pitching movement around the shaft to create hydrodynamic pressure instead of up-and-down movement. The working principle of the Duck can be seen in Ref. (Clément et al., 2002). In 2013 a Duck wave energy conversion system was developed by using many multi-level models of hydraulic systems and were tested by Guangzhou Institute of Energy Conversion in China, having a power generation capacity of 100 kW (Lin et al., 2015b). The hydraulic motor type PTO system-based wave energy convertors have been summarised in

Table 1 indicating the systems that have been developed, deployed and tested in various countries.

Table 1: Hydraulic motor system based WEC

Name of the WEC	**Company Name and Website**	**Deployed Place and Year**	**Location**	**Rated Power**	**Ref.**
Pendulor	Muroran Institute of Technology (https://www.muroran-it.ac.jp/en/)	Japan (1983)	Shoreline	5 kW	(Beirão, 2007)
Kaiyo	Japan Institute for Shipbuilding Advancement (----)	Japan (1984)	Offshore	10 kW	(Lindroth and Leijon, 2011)
McCabe Wave Pump	Hydam Technology Limited (--)	Ireland (1996)	Offshore	400 kW	(Jackson and Boxx, 2012)
EB Frond	Lancaster University (www.lancaster.ac.uk/)	UK (2003)	Offshore	263 kW	(New et al., 2005)
PS Frog	Lancaster University (www.lancaster.ac.uk/)	UK (2005)	Offshore	2 MW	(McCabe et al., 2006)
SEAREV	Ecole Centrale de Nantes (www.ec-nantes.fr/)	France (2006)	Offshore	0.5 MW	(Clément et al., 2005)
OOB	Guangzhou Institute of Energy Conversion (GIEC) (www.english.giec.cas.cn/)	China (2006)	Onshore	50 kw	(Shi et al., 2015; You et al., 2012)
WEC (FO3)	Fred Olsen Company (www.fredolsen.no/) ABB (https://new.abb.com/)	Norway (2006)	Nearshore	2.52 MW	(Albert Leirbukt, 2006)
Wavebob	Wavebob Ltd (www.vimeo.com/wavebob)	Ireland (2007)	Offshore	1 MW	(Lin et al., 2015b)
Pelamis	Ocean Power Delivery Ltd (www.oceanpd.com)	UK (2009)	Offshore	750 kW	(Lin et al., 2015b)
Wave Star	Wave star A/S (http://wavestarenergy.com/)	Denmark (2009)	Offshore	600 kW	(Hansen et al., 2013a)
SDE	SDE Energy Ltd (www.sde-energy.com/)	Israel (2010)	Shoreline	40 kW	(Poullikkas, 2014)
Langlee Wave Power	Langlee Wave Power (www.langleewp.com/)	Denmark (2011)	Offshore	132 kW	(Pecher et al., 2010)
SyncWave Power Resonator	SyncWave (www.naturefirstusa.org/Special%20Reports/Ocean%20Energy/SyncWave%20Systems.htm)	Canada (2011)	Nearshore	25 kW	(Ventures, 2009)
WaveNET	Albatern (www.albatern.co.uk/)	Scotland (2012)	Offshore	7.5 kW	(Albatern, 2014)
Wave Roller	AW-Energy (www.aw-energy.com/)	Portugal (2012)	Offshore	300 kW	(Lin et al., 2015b)
Duck	Guangzhou Institute of Energy Conversion (www.english.giec.cas.cn/)	China (2013)	Offshore	100 kW	(Lin et al., 2015b)
OHS	Atmocean Inc (www.atmocean.com/)	UK (2014)	Offshore	249 kW	(James R Joubert, 2013)
CCell	Zyba Renewables (www.ccell.co.uk/)	UK (2015)	Nearshore & offshore	20 kW	(Sell et al., 2018)
Sharp Eagle	Guangzhou Institute of Energy Conversion (http://english.giec.cas.cn/)	China (2015)	Nearshore	100 kW	(Sheng et al., 2017)
BioWave	BioPower Systems Pty Ltd (www.bps.energy/)	Australia (2015)	Offshore	250 kW	(Council, 2016)
Triton	Oscilla Power (www.oscillapower.com/triton-wec/)	US (2016)	Offshore	600 kW	(OSCILLAPower, 2019)
Sharp Eagle	Guangzhou Institute of Energy Conversion (http://english.giec.cas.cn/)	China (2018)	Nearshore	120 kW	(MELO, 2018)
Azura	Northwest energy innovations (NWEL) (http://azurawave.com/)	USA (2018)	Nearshore	20 kW	(OES, 2018a)
DEXA WEC	DEXA Wave ApS (www.dexawave.com/)	Denmark (--)	Nearshore	160 kW	(Ruol et al., 2011)

FLOW	Martifer Energy (www.martifer.pt/)	Portugal (--)	Nearshore	1.5-2MW	(Fonseca et al., 2010; James R Joubert, 2013)

Figure 3: Wave Roller (WAVEROLLER, 2018)

Figure 4: Duck (Lin et al., 2015b)

2.1.1 Benefits and Challenges of the Hydraulic motor systems

Because of the large power density of the waves and being suitable for low-frequency operation, the hydraulic motor-based PTO system has significant advantages (Gaspar et al., 2016). The hydraulic motor can generate large amounts of power from the low frequency waves and can be used effectively to extract energy from the continuous variation of the wave energy converter movement. Generally, waves create large forces with slow speed and in these conditions the hydraulic system is very suitable and effective to harvest energy (Drew et al., 2009; Henderson, 2006; Zhang et al., 2012). The hydraulic motor system usually uses incompressible fluid which can help to deliver higher efficiency. The overall claimed efficiency of the system varied from 69% to 80% but in the real-world it would have a lower efficiency (Hansen et al., 2013b). In addition, with the aim of maximising energy absorption along with the ocean wave condition the hydraulic motor system can also be used to control the WEC device (António, 2007). The components needed to assemble the hydraulic motor system are locally available from hydraulic components suppliers (Lasa et al., 2012).

The fluid flows inside the hydraulic system due to compression and decompression of the fluid in the hydraulic actuator chamber and this can create hydraulic oil leakage (Zou and Abdelkhalik, 2018), which can harm the marine environment. The hydraulic motor-based PTO system consists of a lot of mechanical moving parts therefore its structure is complex and it needs regular system maintenance in ocean environment which is costly, risky and time consuming (Drew et al., 2009). Moreover, another challenge of the hydraulic motor-based PTO system is the end-stop problem. The hydraulic actuator can exceed its maximum displacement limit and can damage the system due to unexpected extreme conditions (Jusoh et al., 2019).

2.2 Pneumatic air turbine transfer system

Pneumatic air turbine transfer system is another very well-known type of PTO system for WEC. Generally, the compressed air drives the air turbine in the system and the turbine directly drives the generator to generate energy. The schematic of the air turbine transfer based PTO system has been shown in Figure 5. The air turbine is usually used in the oscillating water column (OWC) type and breakwater integrated OWCs wave energy convertor.

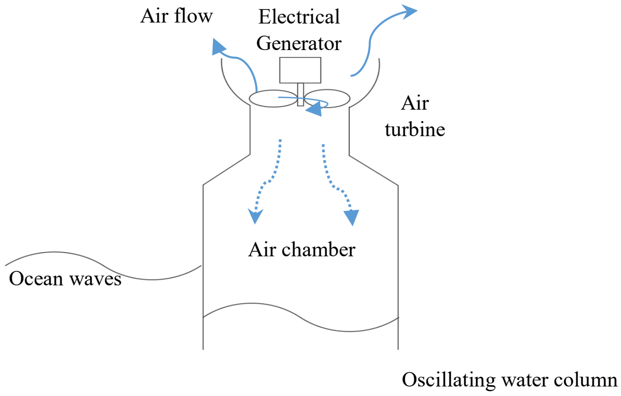

Figure 5: Schematic of the air turbine based PTO system (Têtu, 2017)

Comprehensive reviews of the air turbine for wave energy conversion can be found in (Falcão and Henriques, 2016; Setoguchi et al., 2001; Setoguchi and Takao, 2001, 2006; Takao and Setoguchi, 2012). Iraide López et al (López et al., 2013) introduced some air turbines for WECs. The sea water in the wave energy converter system creates pressure in the air and this pressurised air runs directly through the turbine coupled with the generator to generate energy. Wells and impulse turbines are common types of air turbine designs which are widely used in wave energy convertors with or without fixed or variable guide blades. Toshiaki Setoguchi and Manabu Takao (Setoguchi and Takao, 2006; Takao and Setoguchi, 2012) summarised different types of air turbines which can be used in wave energy converters to generate energy from ocean waves. So far there are many WECs that have been developed based on air turbine systems. Table 2 presents a listing of the installed prototype WEC devices around the world, based on the use of the Pneumatic air turbine transfer system, in offshore, onshore and nearshore locations. Limpet, known as an oscillating water column type device, is the most well-known and its first commercial WEC was installed in 2000 on the shoreline of the Island of Islay, Scotland and it had the ability to generate about 500kW of power for the national grid since installation (Brekken, 2011; Falcão and Henriques, 2016). Limpet consists of special types of turbines to generate energy from compressed air, generated from the incoming waves due to rises and falls of the water level inside the water chamber.

Table 2: Pneumatic air turbine transfer system based WEC

Name of the WEC	Company Name and website	Deployed Place and Year	Location	Power Capacity	Ref.
Sanze shoreline gully	Sanze shoreline gully (--)	Japan (1984)	Onshore	40 kW	(Brooke, 2003)
Kaimei	Japan Marine Science and Technology Centre (JAMSTEC) (https://www.jamstec.go.jp/e/)	Japan (1985)	Offshore	60-125 kW	(Lindroth and Leijon, 2011)
Multiresonant OWC	Kvaerner Brug's (www.kvaerner.com/)	Norway (1987)	Onshore	500 kW	(Malmo and Reitan, 1986)
Bottom-standing OW	Ocean Engineering Centre of the Indian Institute of Technology (www.doe.iitm.ac.in/)	India (1990)	Nearshore	125 kW	(Ravindran and Koola, 1991)
Vizhinjam OWC	National Institute of Ocean Technology (NIOT) (www.niot.res.in/)	India (1991)	Onshore	10 kW	(Falcão and Henriques, 2016)
Sakata	Japanese Ministry of Transport (---)	Japan (1992)	Nearshore	60 KW	(Falcão and Henriques, 2016)
Osprey	Wavegen (www.wavegen.co.uk/) (http://www.eve.eus/index.aspx	UK (1995)	Nearshore	2 MW	(Falcão and Henriques, 2016)
Mighty Whale	JAMSTEC (www.jamstec.go.jp/e/)	Japan (2000)	Offshore	110 kW	(Hotta et al., 1996)

LIMPET	Wavegen Ltd (www.eve.eus/index.aspx)	Scotland (2001)	Onshore	500 kW	(Lin et al., 2015b)
Onshore OWC	Guangzhou Institute of Energy Conversion (GIEC) (www.english.giec.cas.cn/)	China (2001)	Onshore	100 kW	(Falcão and Henriques, 2016)
Tunneled Wave Power Plant	SEWAVE Ltd (http://www.sewave.fo/)	Denmark (2003)	Onshore	---	(Bremerhaven, 2006)
Port Kembla OWC	Oceanlinx (Energetech) (www.oceantecenergy.com/)	Australia (2005)	Nearshore	500 kW	(Robertson, 2014)
Pico	Instituto Superior Tecnico (www.pico-owc.net/)	Portugal (2005)	Nearshore	400 kW	(Falcão and Henriques, 2016)
OE buoy	Ocean Energy Limited (www.oceanenergy.ie/)	Ireland (2008)	Offshore	1 MW	(Falcão and Henriques, 2016)
Oceantec	Oceantec (www.oceantecenergy.com/)	Spain (2008)	Offshore	500 kW	(James R Joubert, 2013)
AWS-iii	AWS Ocean Energy (www.awsocean.com/)	UK (Scotland) (2010)	Offshore	2.5 MW	(SUBSEA, 2014)
Mutriku	Wavegen (www.eve.eus/index.aspx)	Spain (2011)	Nearshore	300 kW	(Technology, 2019c)
REWEC3	Wavenergy.it (www.wavenergy.it/)	Italy (2012)	Onshore	--	(Arena et al., 2013)
Vert Labs	Vert labs (---)	Scotland (2012)	Offshore	35 kW	(James R Joubert, 2013)
Oceanlinx	GreenWave (https://www.greenwave.org/) Oceanlinx (www.oceanlinx.com/)	Australia (2013)	Offshore	1MW	(Doyle and Aggidis, 2019)
OWEL	Offshore Wave Energy Ltd. (OWEL) (----)	UK (2013)	Offshore	12 MW	(James R Joubert, 2013)
Bombora	Bombora Wave Power (www.bomborawave.com/)	Australia (2015)	Nearshore	60MW	(ARENA)
LEANCON	LEANCON Wave Energy (http://leancon.com/index.html)	Denmark 2015	Offshore	300-1500 kW	(Device, 2019)
Oceantec	Oceantec (www.oceantecenergy.com/)	Spain (2016)	Offshore	30 kW	(Magagna et al., 2016)
Wave Clapper	Eco Wave Power (https://www.ecowavepower.com/)	Gibraltar (2016)	Onshore	100kw (modular)	(Magagna et al., 2016)
MARMOK-A-5	Opera (http://opera-h2020.eu/#Contact)	Spain (2016)	Offshore	30 kW	(REN21, 2018)
Yongsoo WEc	(----)	Korea (2017)	Nearshore	500 kW	(OES, 2017)
Symphony	Teamwork Technology B.V (www.teamwork.nl) (https://symphonywavepower.com/)	Portugal (2018)	Offshore	---	(DMEC, 2019)
OE35	Ocean Energy USA LLC https://oceanenergy.ie/ocean-energy-usa/ocean-energy-usa-llc/	USA (2019)	Offshore	500 kW	(Lewis, 2019)
Wave Swell	Wave Swell Energy (https://www.waveswell.com/technology/)	Australia (2019)	Nearshore	200 kW	(Swell, 2020)
MRC 1000	OreCon (---)	UK (---)	Offshore	1 MW	(Bedard and Hagerman, 2004)
SWEC	University of Stellenbosch (http://www.sun.ac.za/english)	South Africa (----)	Nearshore	5 MW	(Joubert and Van Niekerk, 2009)
Isle of Islay	Queen's University of Belfast (http://www.qub.ac.uk/)	Scotland (----)	Nearshore	75 kW	(Falcão and Henriques, 2016)
Etymol	ETYMOL Ocean Power (www.etymol.com/intro.html)	Chile (---)	Offshore	4 MW	(M., 2018)
SPERBOY	Embley Energy (http://www.sperboy.com/)	Ireland (---)	Offshore	450 kW	(De Rijcke, 2019)
Pneumatically Stabilized Platform	Float Inc (http://www.floatinc.com/Default.aspx)	US (---)	Nearshore	---	(Inc, 2016)

Caisson OWC	Saga University (http://www.saga-u.ac.jp/)	Japan (---)	Onshore	---	(Khan and Bhuyan, 2009)

Moreover, the Netherlands wave developer company Teamwork Technology B.V (www.teamwork.nl) designed and developed a new wave energy converter based on the Archimedes Wave Swing (AWS) that was known as Symphony (DMEC, 2019). The new developed Symphony consists of a multifunctional membrane and a novel turbine. Currently, the Symphony system is still under development and is waiting for deployment.

2.2.1 Advantages and challenges of pneumatic air turbine transfer system-based PTO systems

The advantage of using air as the working fluid for WEC is to increase the wave's slow velocities into high air flow rates. The pneumatic air turbine transfer system does not have environmental impact like the hydraulic motor-based PTO systems, as the air turbine is used to harness energy from the high air flow, which has been a mature technology for many decades. The benefits of the air turbines are that they can be located away from the potentially corrosive salt water and destructive high waves, not being in direct contact with them; they can also be located to be easily accessible for maintenance (Soares et al., 2012). However, conventional turbines are not suitable because of the bidirectional flow. Non-return valves coupled with a traditional turbine are a possible solution to this problem, but the non-return valve airflow rectification system is complicated and hard to maintain. In fact, in a large-scale wave energy unit, such a system cannot be implemented because the valve is large (Maria-Arenas et al., 2019; Pecher and Kofoed, 2017). Due to its ability to rotate in the same direction, regardless of airflow direction, the Wells turbine is the most popular pneumatic air turbine transfer system design. The major disadvantage of the Wells turbine is that it is not self-starting: an external source is needed to initially drive the rotor (Pecher and Kofoed, 2017). The claimed efficiency (around 60-65%) of the Wells turbine is also lower than the traditional turbine system (Drew et al., 2009; Takao and Setoguchi, 2012). It also has high axial thrust and high noise compared to the traditional system (Kim et al., 2001; Takao and Setoguchi, 2012). Moreover, the extra function increases the turbine's number of moving parts, thus reducing stability and increasing the turbine's operating and maintenance costs.

2.3 Hydro turbine transfer system

In the hydro turbine transfer system normally the compressed water runs the hydro turbine and the turbine directly drives the generator to generate energy as shown in Figure 6. A hydro turbine is normally used in the overtopping type of wave energy convertor. There are some designed hydro turbines for WECS that have been introduced in Ref. (López et al., 2013).

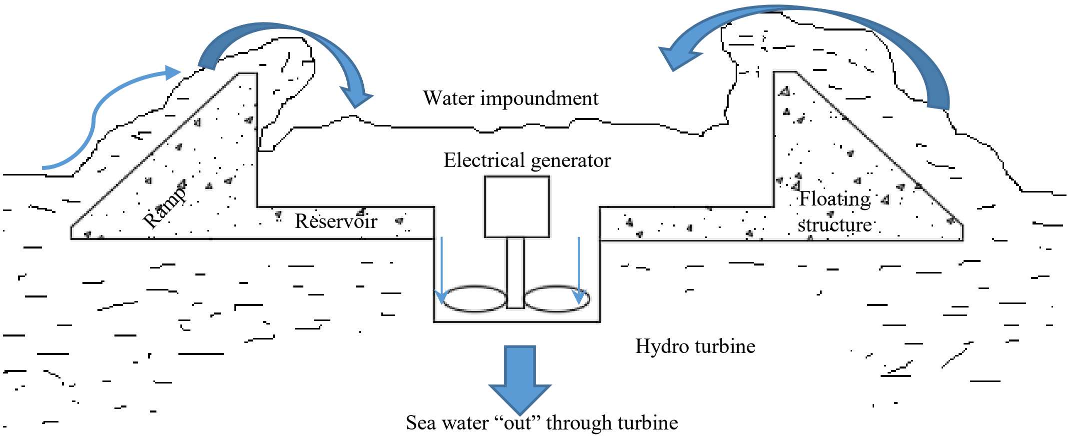

Figure 6: Schematic of the hydro turbine based PTO system (Tutorials, 2019)

A Danish company named Wave Dragon Aps developed and installed the Wave Dragon (Figure 7) device in 2003 in Nissum Bredning, Denmark, which is an overtopping type device and was the first offshore floating slack-moored WEC in the world (Parmeggiani et al., 2011; Polinder and Scuotto, 2005). Some EU countries including Denmark, the UK, Portugal, Germany, Sweden, Austria and Ireland jointly supported this Wave Dragon project. The device consists of two arms that assist water to gather in the reservoir, whose level is higher than the surface level of the ocean and turbine by using a submerged ramp. The stored water is then moved back to the sea via channels that run the turbine to generate energy, located in the middle position of the reservoir.

Figure 7: Wave Dragon (COPYBOOK, 2019)

The WaveCat also developed an overtopping concept like the wave Dragon (Fernandez et al., 2012).

A new wave energy technology CETO 5 prototype with 5MW peak design capacity, developed by Carnegie has been installed in Fremantle between Garden Island and the Five Fathom Bank, Perth, Western Australia, which was the world’s first wave energy project that produced energy and desalinated water together in the same time at commercial scale (Australian Renewable Energy Agency, 2018). The project work started in 2010 and was completed by 2015 and connected with the grid to provide power for around 3,500 homes (Power Technology, 2018). To harness energy from waves, the CETO system uses buoys and the pressure difference of the buoy forces the piston inside the hydraulic cylinder to move and push the water through underwater pipes that then drive a hydroelectric turbine to generate electricity as well as desalted water through reverse osmosis. Hydro turbine methods have also been used in the Aquabuoy, as can be seen in Figure 8, to generate energy from ocean waves in the USA (Retzler, 2006; Weinstein et al., 2004). In the Aquabuoy the pumped water was directed into a conversion system that consists of a Pelton turbine to drive a conventional electrical generator. Table 3 shows the hydro turbine based WECs with their power capacity, which has been proposed and installed in different countries in the world. It also shows that a larger portion of the existing WEC projects based on the hydro turbine have been installed offshore.

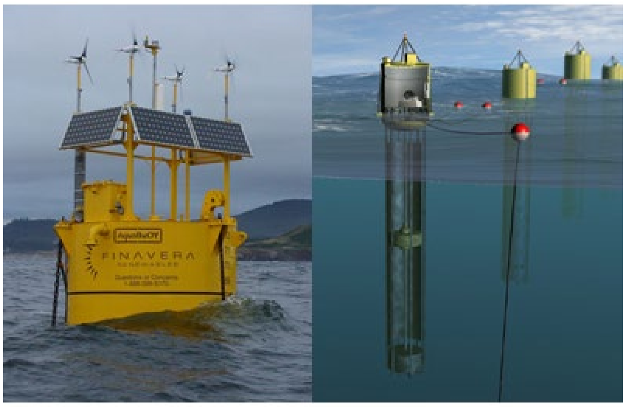

Figure 8: AquaBuOY (Munteanu, 2015)

Table 3: Hydro turbine based WEC

Name of the WEC	*Company Name and website*	*Deployed Place and Year*	*Location*	*Power Capacity*	*Ref.*
TAPCHAN	Norwave AS (---)	Norway (1985)	Onshore	350 kW	(Poullikkas, 2014)
CONWEC	Norwegian University of Science and Technology (https://www.ntnu.edu/)	Norway (1988)	Nearshore	300 kW	(Falnes, 2005)
Wave Dragon	Wave Dragon Aps (http://www.wavedragon.net/)	Denmark (2003)	Offshore	7 MW	(Lin et al., 2015b)
AquaBuOY	Finavera Wind Energy (http://www.finavera.com/) later SSE Renewables Limited (https://sse.com/whatwedo/sse-renewables/)	Ireland-Canada-Scotland (2003)	Offshore	2.5 MW	(Fadaeenejad et al., 2014)
SSG	WaveEnergy (https://www.waveenergy.no/)	Norway (2004)	Onshore	150 kW	(Margheritini et al., 2009)
CycWEC	Atargis Energy Corporation (https://atargis.com/index.html)	USA (2006)	Offshore	5 MW	(James R Joubert, 2013)
Ocean Energy Buoy	Ocean Energy Ltd (http://www.oceanenergy.ie/)	Ireland (2007)	Offshore	150 kW	(Tethys, 2014)
Anaconda	Checkmate SeaEnergy UK Ltd (https://www.checkmateukseaenergy.com/)	UK (2008)	Offshore	1 MW	(Council, 2008)
Power Buoy	Ocean Power Technologies (https://www.oceanpowertechnologies.com/)	Spain (2008)	Offshore	40 kW	(Antonio, 2010)
Power Buoy	Ocean Power Technologies (https://www.oceanpowertechnologies.com/)	Scotland (2009)	Offshore	150 kW	(Antonio, 2010)
Power Buoy	Ocean Power Technologies (https://www.oceanpowertechnologies.com/)	USA (2011)	Offshore	150 kW	(Lin et al., 2015b)
Oyster	Aquamarine Power (http://www.aquamarinepower.com/)	Scotland (2012)	Nearshore	800 kW	(Lin et al., 2015b)
FlanSea	FlanSea (http://www.flansea.eu/)	Belgium (2013)	Offshore	1 kW	(LUDOVIC MOUFFE, 2016)

Wavepiston	Wavepiston Aps (https://www.wavepiston.dk/)	Denmark (2013)	Offshore	250 kW	(MarineEnergy.biz, 2016)
Vigor WEC	Vigor Wave Energy AB (----)	Sweden (2014)	Offshore	12 MW	(Gürsel et al., 2016)
CETO	Carnegie Wave Energy Ltd (https://www.carnegiece.com/)	Australia (2015)	Offshore	1 MW	(Australian Renewable Energy Agency, 2018)
Atmocean	Atmocean Inc. (https://atmocean.com/)	Peru (2015)	Nearshore & offshore	--	(ATMOCEAN, 2019)
WaveEL	Waves 4 Power (https://www.waves4power.com/)	Norway (2016)	Offshore	0.2 MW	(Tethys, 2017)
Crown	Ocean University of China (http://www.ouc.edu.cn/)	China (2017)	Offshore	---	(Liu et al., 2017)
Power Buoy PB3	Ocean Power Technologies (https://www.oceanpowertechnologies.com/)	UK (2019)	Offshore	40 kW	(OPT, 2019)
WaveCat	University of Santiago de Compostela (http://www.usc.es/)	Spain (---)	Offshore	--	(Fernandez et al., 2012)
WavePlane	WavePlane Production (http://www.waveplane.com/)	Denmark (---)	Nearshore	200 kW	(James R Joubert, 2013)
OMI Wave Pump	Ocean Motion International (www.oceanmotionintl.com/)	US (--)	Offshore	1.6 MW	(Dwight Houser, 2013)
PowerGin	Kinetic WavePower (http://www.kineticwavepower.com/)	US (--)	Offshore	20 MW	(Ventures, 2017)
Pontoon Power Convertor	Pontoon Power (https://www.pontoon.no/)	Norway (--)	Offshore	15-20 MW	(Pontoon, 2019)

The cycloidal turbine has also been used in PTO systems to harvest energy from waves (Siegel et al., 2009; Siegel et al., 2011). The Cycloidal wave energy converter (CycWEC) has been developed based on the use of the Cycloidal turbine (Siegel et al., 2011). Atargis Energy Corporation developed the 5 MW rated Cycloidal WEC and deployed it in the USA for testing purposes in 2006 (James R Joubert, 2013).

2.3.1 Advantages and challenges of Hydro turbine-based PTO systems

Hydro turbines have the advantage of being a mature technology, where the designs such as the Kaplan turbine have been used for power generation for many decades. It requires low maintenance and can operate with 90 % efficiency (Pecher and Kofoed, 2017). For wave energy conversion, the bottleneck lies in the extraction of energy from ocean waves that can provide enough head and flow to be economical for the Kaplan turbine generator unit. The significant benefit of using the hydro turbine is that no environmental problems are caused by fluid leakage (Drew et al., 2009). The drawback is that ocean water is a dynamic fluid with various unpredictable components. These components can damage the seals and the valves. Cavitation can also be a concern if the turbine is not in deep water to maintain positive pressure.

2.4 Direct mechanical drive systems

Direct mechanical drive systems generated energy by the wave converter directly into electricity by using an electric generator. Usually the mechanical transmission system and gearbox are used to drive the electrical generator which is directly coupled with the gearbox. The schematic of the direct mechanical drive-based PTO system is shown in Figure 9. There are many WEC prototypes based on the direct mechanical drive that have been developed and deployed. Wello Ltd developed and tested a WEC known as the Penguin which used an electric generator to generate energy from waves (Amir et al., 2016).

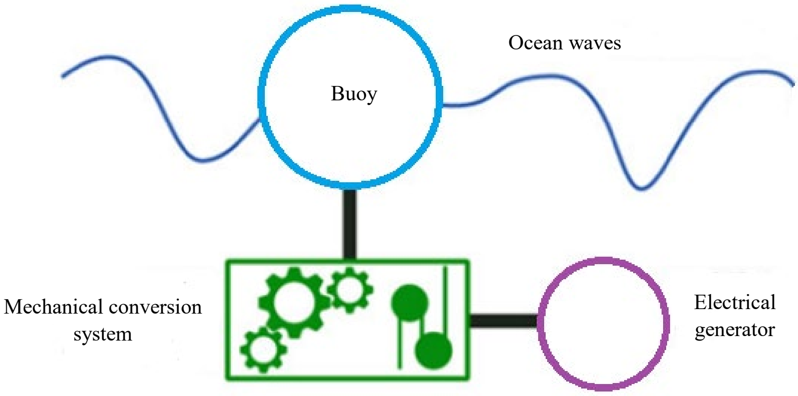

Figure 9: Schematic of the Direct mechanical drive based PTO system (upgrade of Ref. (Têtu, 2017))

The Resen Waves company designed and developed a very light and cost effective WEC known as the Smart Power Buoy as shown in Figure 10 which had the ability to generate 0.3 kW power (Waves, 2017). The device was designed in such a way that it can provide continuous power and real time date connectivity to autonomous instruments and machinery in the ocean. Moreover, Witt Limited has developed a patented, completely scalable technology which generates energy from wave motion by using two pendulums connected to a flywheel by a shaft, where the flywheel connects with the generator (ENERGY, 2020).

Some of the WECs which have used the direct mechanical drive system have been listed in Table 4. From Table 4 the largest number of existing WEC prototypes based on the direct mechanical drive system have been installed offshore.

Figure 10: Smart power buoy (Energy, 2019a)

Table 4: Direct mechanical drive system based WECs

Name of the WEC	Company Name	Deployed Place and Year	Location	Rated Power	Ref.
Manchester Bobber	University of Manchester (https://www.manchester.ac.uk/)	UK (2004)	Offshore	5 MW	(MANCHESTER, 2005)
Penguin	Wello Oy (https://wello.eu/)	Finland (2017)	Offshore	0.5-1 MW	(Amir et al., 2016; Wello, 2018)
BOLT Lifesaver	Fred. Olsen & Co (https://boltseapower.com/)	*UK (2010)*	Offshore	84 kW	(Power, 2019)
Wave Rider	Wave Rider Energy (http://www.waveriderenergy.com.au/)	Australia (2011)	Offshore	1 MW	(McCaskill, 2014)

Squid	Albatern (http://albatern.co.uk/)	*Scotland (2012)*	Offshore	45 kW	(Paschoa, 2014)
INWAVE WEC	INGINE Inc. (http://www.ingine.co.kr/en/)	*Korea (2015)*	Onshore	135 kW	(OES, 2017; Song et al., 2017)
ISWEC	Waves for Energy (http://www.waveforenergy.com/tech/iswec)	*Italy (2016)*	Offshore	100 kW	(OES, 2017)
WaveSurfer	Ocean Energy Industries (http://www.oceanenergyindustries.com/)	*USA (2014)*	Offshore	1 kW	(Gürsel et al., 2016)
Crestwing	Crestwing (https://crestwing.dk/)	*Denmark (2018)*	Offshore	--	(OES, 2018a)
FPWEC	Korea Research Institute of Ship & Ocean Engineering (KRISO) (http://www.kriso.re.kr/)	*Korea (2018)*	Offshore	300 kW	(OES, 2018a)
BOLT Lifesaver	Fred. Olsen & Co (https://boltseapower.com/)	*USA (2018)*	Offshore	10 kW (each PTO unit)	(OES, 2018a)
CorPower WEC	CORPOWER OCEAN (http://www.corpowerocean.com/)	Scotland (2018)	Offshore	10MW	(OCEAN, 2020a)
NEMOS	NEMOS Wave Energy Converter (https://www.nemos.org/waveenergy)	*Germany (2019)*	Offshore/ Nearshore	--	(NEMOS, 2020)
Neptune Wave Engine	Neptune Equipment Corp (https://www.neptunewave.ca/)	Canada (2019)	Nearshore	0.5 Mw	(WAVE. CA, 2020)
LAMWEC	Laminaria (http://www.laminaria.be/technology.html)	Scotland (2019)	Offshore	200 kW	(OES, 2018a)
AMOG	AMOG (https://www.amog.consulting/renewable-energy/amog-wave-energy-device)	UK (2019)	Offshore	75 kW	(AMOG, 2020)
Smart Power Buoy	Resen Waves (http://www.resenwaves.com/)	*Denmark (--)*	Offshore	0.3 kW	(Waves, 2017)
IPS Buoy	Interproject Service AB (IPS) and Technocean (TO) (http://www.ips-ab.com/)	Sweden (--)	Offshore	5-10 MW	(Falcão et al., 2012)
Float Pump	Danish Wave Power (DWP) (https://wavepartnership.dk/)	*Denmark (---)*	Offshore	140 kW	(Partnership, 2019)
Wave Energy Device	Wave Energy Technology- New Zealand (WET-NZ) (http://www.wavenergy.co.nz/)	*New Zealand (--)*	Offshore	0.5 MW	(ENERGY, 2019b)
InfinityWEC	Ocean Harvesting Technology (http://www.oceanharvesting.com/infinitywec-technology/)	*Sweden (--)*	Offshore	*500 kW*	(Technology, 2019a)
CECO	University of Porto (https://sigarra.up.pt/up/pt/web_base.gera_pagina?p_pagina=home)	Portugal (--)	Offshore	---	(Rosa-Santos et al., 2019)

Another new WEC has been developed and tested in Portugal based on the direct mechanical drive system which is known as CECO (Rosa-Santos et al., 2019; Rosa-Santos et al., 2015). The gear-rack system and electric generator have been used in CECO. The novelty of the CECO is that it consists of two floating modules which help to generate electrical energy simultaneously from the kinetic and the potential energy of the ocean waves. The schematic diagram for the CECO PTO system energy generation mechanism has shown in Figure 11. Paulo Rosa-Santos et al reviewed the significant findings and recent developments of the research work of CECO (Rosa-Santos et al., 2019). The current status and future perspectives of the wave energy converter CECO can be seen in Ref. (López et al., 2018)

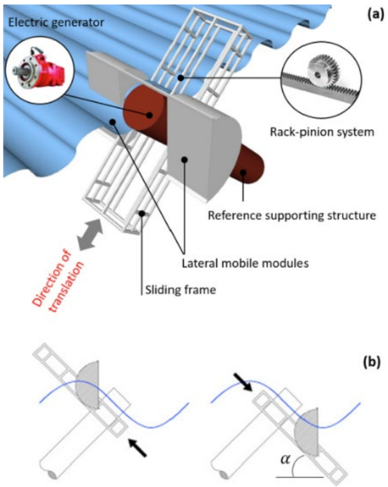

Figure 11: Schematic diagram (a) CECO working mechanism and (b) motion during wave transfer (Rosa-Santos et al., 2019)

2.4.1 Advantages and challenges of direct mechanical drive-based PTO systems

The term “Direct Mechanical Drive” indicates transmitting the wave energy into electrical energy using linear-to-rotary conversion systems without any pneumatics or hydraulic systems. Therefore, the Direct Mechanical Drive wave energy conversion system obtains more wave energy than hydraulic system because of the reduced friction. Numerous traditional transmission mechanisms have been proposed for use in wave energy converters, such as rack and pinion, belt drive system, ratchet wheel or screw mechanisms. One advantage of this type of PTO system is that there is only need for up to three energy conversions, resulting in high performance. The efficiency of the rack and pinion mechanisms is very high, up to 97% being claimed (Penalba and Ringwood, 2016). However, the direct mechanical drive system undergoes higher load cycles, and reliability of this type of system still needs to be proven. The relatively short lifetime and higher maintenance costs is the biggest challenge of the rack and pinions mechanisms. Moreover, the size of the gearbox for WEC devices varies with the shape and size of the system. For example, the outer dimension of the gearbox used in Smart Power Buoy was 300mm x 400mm (diameter) and the cost was USD 1500. On the other hand the cost of the gearing system of one BOLT Lifesaver’s PTO was about £40k (Hjetland, 2020; Steenstrup, 2020).

2.5 Direct linear electrical drive systems

To overcome the mechanical complexity of some of the WEC designs, electromagnetic based linear generators or direct electrical drive systems have been used in PTO systems (Mueller and Baker, 2002; Polinder et al., 2005). The concept of the linear generator, when placed on the seabed, is based on the use of a translator and stator, where the translator is attached to a floating buoy and the stator is fixed or vice versa. The translator consists of permanent magnets, and the stator is equipped with coil windings. The translator moves up and down along with the buoy because of the hydrodynamic action of the ocean waves and creates the magnetic field inside the coil windings, thereby creating the electric power. Figure 12 shows the schematic of the direct electrical drive-based PTO system.

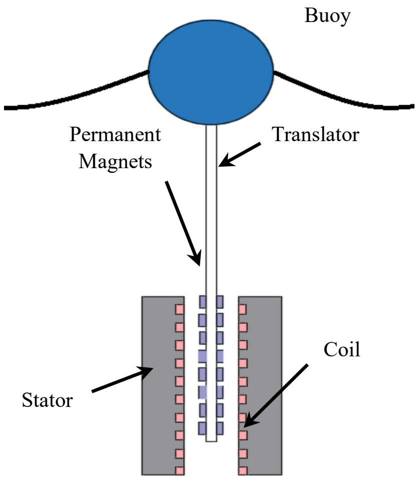

Figure 12: Schematic of the direct electrical drive based PTO system (Drew et al., 2009)

Oregon State University developed 12 prototypes, and deployed and tested them over a period of more than one decade starting in 1998 (Brekken et al., 2009; David Elwood, 2010). The first device contained a spar and a float where the spar was moored, and the float moved up and down with the wave motion. The spar was a central cylindrical design housing a bobbin, wound with a three-phase armature and the float was an outside cylinder that consisted of 960 magnets. The inner surface of the float faced the outer surface of the spar and when the float moved up and down due to the wave motion then voltage was directly produced inside the armature (Prudell et al., 2009; Prudell, 2007). Uppsala University developed around 14 WEC prototypes that were installed at the Lysekil wave research site off the Sweden West Coast from 2002 to the present (Danielsson et al., 2005; Elwood et al., 2010; Hong et al., 2013; Stålberg et al., 2005; Waters, 2008; Waters et al., 2007). These larger WEC designs contained a buoy, translator and stator, where the translator moved up and down with the buoy inside the stator which was fixed to the seabed. The translator was a rectangular shape that consisted of a number of permanent magnets with the stator containing the wound coils (Waters et al., 2007). Another very popular linear generator based WEC was the SINN power wave energy system developed by SINN Power GmbH which consisted of a variable number of buoys that were attached to a fixed steel frame. Due to the wave action the buoys move up and down and generate electricity. The floating bodies of the WEC lift a rod which runs through a generator unit. SINN power deployed a single WEC at nearshore as shown in Figure 13(a) at the Port of Heraklion Crete (Greece) and it is been tested since 2015 (GmbH, 2018; LiVecchi, 2019). The SINN power commercial project (off-grid series) as shown in Figure 13(b) was under preparation in 2017 to be deployed in future (Sinn, 2017). Table 5 shows the list of electromagnetic based WECs which have been installed in different countries, where the analysis indicates that the largest portion of the existing direct electrical drive WEC prototypes have been installed offshore.


(a) (b)

Figure 13: SINN wave energy converter (a) Single device (b) off-grid series (Sinn, 2017)

Table 5: Direct electrical drive system based WECs

Name of the WEC	Company Name	Deployed Place and Year	Location	Rated Power	Ref.
Lysekil Project	Uppsala University (http://www.uu.se/)	Sweden (2002)	Offshore	10 kW	(Leijon et al., 2008)
AWS	AWS Ocean Energy (http://www.awsocean.com/)	Portugal (2004)	Offshore	2 MW	(Antonio, 2010)
Oregon L10	Oregon State University (https://oregonstate.edu/)	USA (2008)	Offshore	10 kW	(Waters et al., 2007)
DCEM	Trident Energy (http://www.tridentenergy.co.uk/)	UK (2008)	Nearshore	100 MW	(James R Joubert, 2013)
SeaRay	Columbia Power Technologies (https://columbiapwr.com/)	USA (2011)	Offshore	1 MW	(Technologies, 2019)
UNDIGEN	Wedge Global	Spain (2014)	Offshore	200 kW	(OES, 2017)
Seabased	Seabased AB (https://www.seabased.com/)	Sweden (2015)	Offshore	1MW	(James R Joubert, 2013)
SINN Power WEC	SINN Power GmbH | Wave Energy (https://www.sinnpower.com/)	Greece (2015)	Nearshore	--	(LiVecchi, 2019)
StingRay	Columbia Power Technologies (C·Power)	USA (2019)	Offshore	500 kW	(OES, 2017)
Brandl Generator	Brandl Motor (http://brandlmotor.de/wellenenergie_eng.htm)	Germany (--)	Offshore	1 MW	(Motor, 2019)
Float Wave Electric Power Station (FWEPS)	Applied Technologies Company (ATC) (http://atecom.ru/)	Russia (--)	Offshore	50 kW	(Temeev)
SEACAP	Hydrocap energy (www.hydrocap.com/)	France (under construction)	Offshore	--	(Hydrocap, 2019)
SEA-TITAN	Hydrocap energy (www.hydrocap.com/)	France (under construction)	Offshore	--	(Hydrocap, 2019)

The UK based wave energy developer company Archimedes Wave Swing (AWS Ocean) designed a series of AWS WECs and they were first deployed and tested in Portugal (AWS, 2019). The AWS is basically a fully submerged air-vessel which was mainly developed in the Netherlands. The Dutch company Teamwork Technology first conceived of the original concept of the AWS. It consists of two parts; the top part is free to move but the bottom part is fixed to the seabed. The floating component moves up and down because of the water pressure which is created as the wave passes over the AWS. The linear generator generates energy from this relative motion between the top and bottom parts. The AWS was the first commercial wave energy converter that used a linear electrical generator in a PTO system.

2.5.1 Advantages and challenges of direct electrical drive-based PTO system

The word "Direct electrical Drive" indicates transmitting the wave energy into electrical energy directly without any pneumatics or complex linear-to-rotary conversion systems. This device directly couples the mechanical energy collected by the primary converter to the moving part of a linear generator (Baker and Mueller, 2001; Mueller, 2002). That means this system has the advantage of not requiring an intermediate mechanical interface (for example a gearbox) and thus avoids the losses that take place in other PTO systems (turbines and hydraulic motors) which consequently reduces maintenance cost (Hong et al., 2014; Leijon et al., 2008; Muetze and Vining, 2006). The main advantages of direct electric drive systems (linear permanent magnet generators) are a relatively high efficiency and the possibility of continuous force control (Danielsson, 2006). In addition, this PTO system needs power electronics in order to convert the generated electricity to a form that is suitable for the electric grid (Hong et al., 2014). The main disadvantage of linear generators is that the linear velocity of the translator, determined by the velocity of the absorber, is much lower than conventional rotary generators' equivalent rotational velocity due to low frequencies of the ocean waves. Other drawbacks are the low power-to-weight ratio (very large machines are needed) and the need for a heavy structure due to the attractive forces between the stator and the translator (Penalba and Ringwood, 2016). Moreover, the power transmission system is very complicated due to the unequal generated voltage created by the irregular wave motion (Leijon et al., 2008).

2.6 Triboelectric Nanogenerators

The triboelectric nanogenerator (TENG) was invented in January 2012 based on the coupling of triboelectrification and electrostatic induction which have specific merits of high power density, high efficiency, low weight and low manufacturing costs (Fan et al., 2012). This TENG can provide a new wave energy conversion method and has potential for large-scale, ocean related blue energy harvesting (Wang, 2015). Over the last couple of years, researchers have been investigating the use of triboelectric nanogenerators (TENGs) in PTO systems to increase the efficiency and reduce the cost (Chen et al., 2015; Khan and Kim, 2016). Newly invented TENGs consist of the use of various conventional materials such as aluminium, polytetrafluoroethylene (PTFE), because they are lightweight, relatively low-cost, easy to fabricate and easy to be scaled up (Wang, 2013, 2015). Two materials create electrostatic induction resulting from the two surfaces where the contact electrification of the two materials helps to transfer charge between their electrodes and the polymer and the metal pair is normally used as the friction layer (Fan et al., 2012; Hinchet et al., 2015; Zhang et al., 2013).

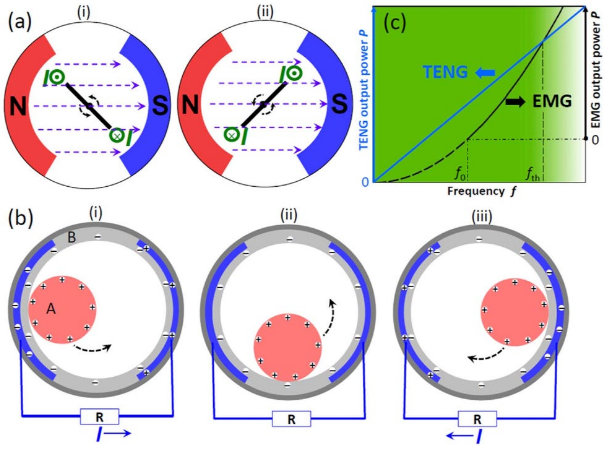

Figure 14: Working Principle (a) electromagnetic generator, (b) TENG coupling triboelectrificatioin effect and electrostatic induction (c) Output comparison between EMG and TENG (Wang et al., 2017)

The working mechanism of TENG is shown in Figure 14(b) and its performance in the low frequency range is shown in Figure 14(c). The interaction between two materials A and B produces electrostatic surface charges; the rolling of the ball changes the system's capacitance, therefore creating the inflow of electrons between the two electrodes to balancing the electrical potential drop (as shown in Figure 14 (b): (i), (ii) and (iii)). A TENGs based wave energy converter is shown in Figure 15. Researchers have shown that this new type of wave energy converter can deliver high energy efficiency (Lin et al., 2015a). Wang et al reviewed the recent progress of the TENG technology in blue energy harvesting (Wang et al., 2017). The fundamental mechanism, structural designs and performance optimizations of TENG for wave energy converter have been discussed as well.

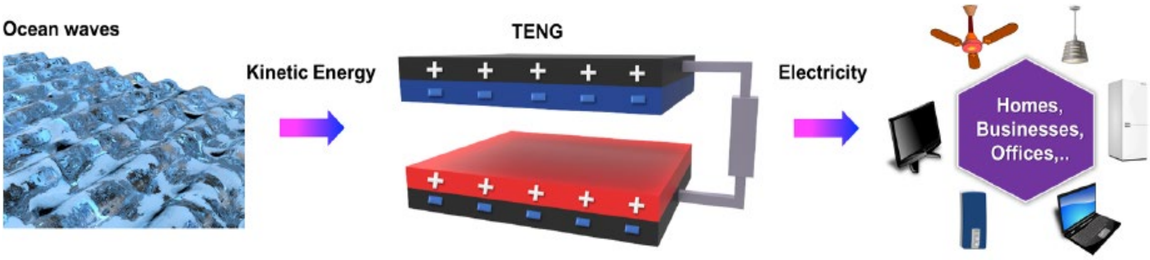

Figure 15: Triboelectric nanogenerator based wave energy converter (Khan and Kim, 2016)

2.6.1 Advantages and challenges of Triboelectric nanogenerators based PTO system

Triboelectric nanogenerator based PTO systems generally use a polymer-metal pair as the friction layer to create contact electrification between two materials and charge transfer between their electrodes due to electrostatic induction (Zhang et al., 2013). These are therefore low cost, lightweight, easy to fabricate, easy to be scaled up and provide a variety of materials to choose from (Wang et al., 2015). In addition, this type of system can have claimed energy conversion efficiencies of up to 55 percent like as electromagnetic generators and have the ability to adapt to various types of mechanical energy in the form of different operational modes such as contact-separation mode, single-electrode mode, sliding mode and freestanding mode (Wang, 2015, 2017). The main advantage of the Triboelectric nanogenerators based PTO system is that it can harvest energy in any frequency range (broad frequency range) (Wen et al., 2016). However, on the other hand, many big challenges lie in the use of TENGs such as power transfer to the shore, device lifetime in the ocean environment, cost to scale and management of large networks of devices (Wang et al., 2017).

2.7 Hybrid systems

Generally, hybrid type PTO systems consist of two or more different types of working techniques or PTO systems to harvest energy from the ocean waves. Based on the use of the triboelectric nanogenerator and electromagnetic generator or piezoelectric materials, there are several WECs that have been proposed as well. Feng et al (Feng et al., 2018) proposed a new type of wave energy harvester based on a triboelectric nanogenerator (TENG) and an electromagnetic generator (EMG) where the TENG generator contains three honeycomb-like electrodes which are covered by PTFE (seven hexagonal films in three groups) and magnets and the EMG consists of seven copper coils which are fixed below the seven electrodes at the back of the acrylic board, as shown in Figure 16. A similar type of system has been proposed by Zia Saadatnia et al (Saadatnia et al., 2018) by using the triboelectric generator (TENG) and electromagnetic generator (EMG) where the floating buoy was used to move the slider. These types of wave energy systems can harvest kinetic and potential energy over a wide range of frequencies and work very efficiently.

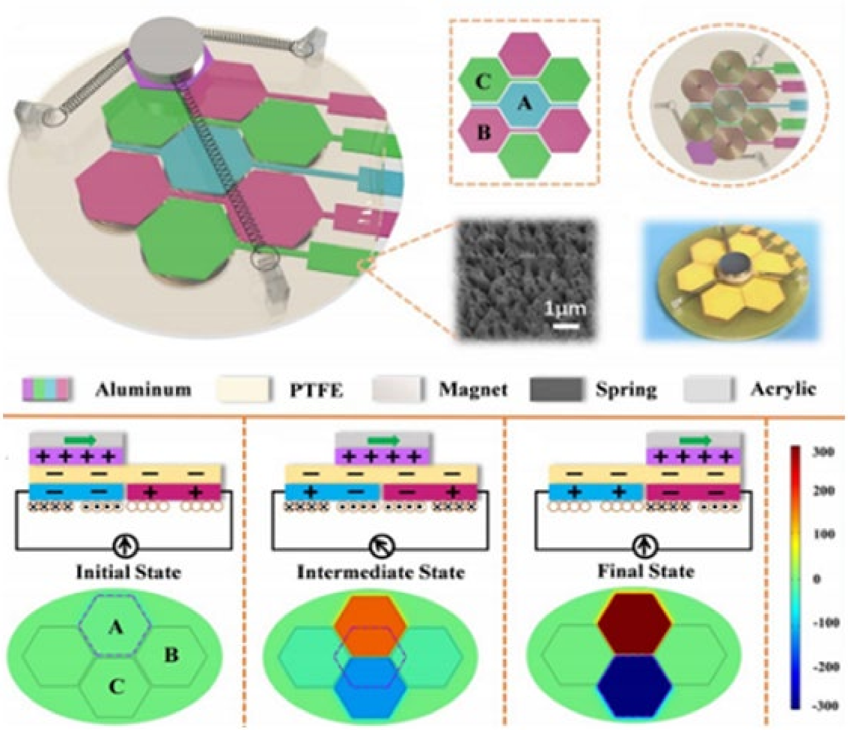

Figure 16: Design of the new system structure (Feng et al., 2018)

Moreover, Offshore wind turbines and wave energy converters working together is also known as hybrid concept as shown in Figure 17, where the wind turbine generates energy from the wind on the ocean surface and the wave converter generates energy from the ocean waves (Kim et al., 2015; Pérez-Collazo et al., 2015; Rusu and Onea, 2018). Photovoltaic-wave energy and wind-photovoltaic-wave energy concepts have also been proposed by some researchers to increase the efficiency of the system (El-Sayed and Sharaf, 2011; Samrat et al., 2014; ZHANG et al., 2004). The hybrid system is a very recent research topic in the field of wave energy and wind energy research and only a limited number of articles have been published (Fusco et al., 2010; Veigas et al., 2014a; Veigas and Iglesias, 2013, 2015; Veigas et al., 2014b). Some researchers have tried to review the previous works and different alternatives techniques which can be used to make hybrid wave energy systems (Kim et al., 2015; Pérez-Collazo et al., 2015). Carlos Perez-Collazo et al (Perez-Collazo et al., 2018) proposed a hybrid system for jacket-frame offshore wind substructures. The proposed hybrid system combines an oscillating water column (OWC) type WEC with jacket-frame offshore wind substructures. Generally, the hybrid systems currently being proposed (research and development levels) are based on fixed (mooring) and floating structure (Kim et al., 2015). There are a couple of hybrid wave-wind systems that have been proposed in some countries. Green Ocean energy, a marine energy company based in Scotland, is developing a wave-wind energy device known as Wave Tender (as shown in Figure 18) and currently, it is projected to have a peak rating of 500kW to 700kW due to high yield per unit of sea area (Technology, 2019b). The system consists of wind turbines to generate energy from the air in the top of the ocean surface and hydraulic cylinders to convert wave energy. A Poseidon system demonstrator has been constructed by the Danish company Floating Power Plant in which a range of pitching type WECs are mounted on a secure cross-type base (Ding et al., 2015). Moreover, a Norwegian company is developing a W2power system that incorporates a point-absorber type WEC and two wind turbines (Ding et al., 2015).

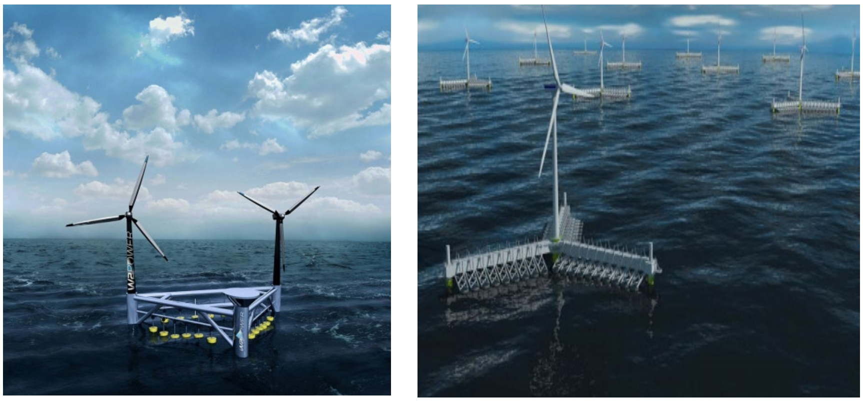
(a) (b)

Figure 17: Hybrid system concepts (a) courtesy of Pelagic Power AS (b) Courtesy of Wave Star AS (Pérez-Collazo et al., 2015)

Figure 18: Wave treader (Rusu and Onea, 2018)

2.7.1 Advantages and challenges of Hybrid system

The main advantage of the hybrid system is its cost saving structure because two working principles to harvest energy can couple with one structure which will reduce the installation and mooring cost. For example, the Hybrid system combining either a floating or mooring wind turbine with wave energy converters in order to harvest energy from the offshore area will reduce the initial investments required compared to the two independent systems. By using the hybrid concept, the new or existing wind turbine infrastructure could be developed as a hybrid system (Manasseh et al., 2017). Therefore, the overall cost of installation, operation and maintenance can be decreased. Moreover, the wave energy converters (WECs) should be incorporated into the platform's overall motion response, thus having a stabilising effect on the entire device (Ding et al., 2015). The hybrid system can deliver higher power efficiency and it have a smoother integration into the grid network, by being less influenced by a single resource's variability (Rusu and Onea, 2018). In addition, by sharing the grid connection, logistics, and the same infrastructure, offshore wind farms could reduce the energy cost of the wave energy. However, because of the one working principle the other working system's performances could be changed because of the mechanical and hydrodynamic couplings. Such as, if the wave energy converter couples with the floating wind turbine then due to the mechanical and hydrodynamic couplings between the floating bodies, the behaviour of the floating wind turbine would be changed (Ding et al., 2015). Therefore, the efficiency of the floating wind turbine could be reduced. Moreover, the two working systems will increase the loads on the structure. Coupling a wave energy converter with a floating wind turbine will also increase the loads of the substructure (Perez-Collazo et al., 2018).

2.8 Other systems

There are various other methods such as the use of piezoelectric materials that have also been used as PTO systems to harvest energy from waves (Hwang et al., 2017; Wu et al., 2015). Hidemi Mutsuda et al (Mutsuda et al., 2019) also proposed a device based on piezoelectric materials to harvest energy from the ocean wave. The proposed device consisted of a laminated structure by using elastic materials and a piezoelectric paint which can easily deform in the presence of external forces such as wind, waves and other forces. SBM has developed and tested a new type of WEC known as S3 where Electro Active polymers (EAP) have been used in the PTO system (Babarit et al., 2013b; Jean et al., 2012). The new WEC can convert energy directly from ocean waves with distributed power generation. The EAP and roll-to-roll process have been used in the PTO system. Figure 19 presents the EAP generator.

Figure 19: EAP Generator (SBM, 2019)

2.8.1 Advantages and challenges of Other systems

The piezoelectric energy harvesting system's energy density is three times higher than the electromagnetic energy harvesting system, and it occupies smaller space than turbine transductions (Nabavi et al., 2018; Priya, 2007). The piezoelectric material based ocean wave energy device, being smaller and lighter, can generate energy from low-frequency wave range in a variety of water motions (Hwang et al., 2017; Su et al., 2014). Moreover, the piezoelectric materials can be easily integrated into the device, having no moving parts, and therefore do not require frequent maintenance (Jbaily and Yeung, 2015). The disadvantages of the piezoelectric energy harvesting system are that the systems are mostly complex, costly, and work well only with shallow ocean waves (Viet et al., 2016). The energy efficiency is also very low compared to electromagnetic and triboelectric nanogenerators because of the energy transduction principal. These methods often convert less than 10% of the available ocean energy into electricity (Wang, 2017).

The fabrication and installation costs of the EAP generator based WEC are low compared with other conventional WECs because the PTO system is also the structure of the device and it can be run until failure (Babarit et al., 2013a). This type of device can avoid the stress concentration and flexible due to the PTO system being distributed over the whole surface (Babarit et al., 2013a). Without moving mechanical parts this device can generate electricity directly from ocean waves (Wattez and van Kessel, 2016). It acts like an antenna which amplifies the dynamic pressure of the ocean waves and it has high number of degrees of freedom and therefore high number of resonance modes which helps to generate energy in any condition period of the waves in any frequency range (Andritsch et al., 2012; Jean et al., 2012). This device is still in the research and development phase and work continues to address the key challenges (Wattez and van Kessel, 2016). The key challenges of the EAP generator based WEC are that the system should be operated at field strengths above 50 V/μm to optimise the maximum energy because of the flexible nature of the system (Andritsch et al., 2012). The lifetime of the device is low compared to the conventional WECs due to the use of segmented electrodes (Jean et al., 2012). Moreover, this device can be destroyed in survival conditions and the fatigue life can be reduced as it operates under combined mechanical and electrical load cycles (Babarit et al., 2013a).

3. Research and development

The WECs are designed to harness energy from the low frequency motions of ocean waves. While a wide number of WECs have been designed over the last few decades, their concepts of extracting waves are identical. By using the PTO system, the absorbed energy is transformed into usable electricity. Therefore, the PTO system is very important in the WEC device because it not only directly affects how effectively the captured wave energy is converted into electricity, but also determines the WEC's mass, size and structural dynamics (Têtu, 2017). The PTO system has direct effect on power conversion efficiency and the levelling cost of energy (LCOE) by providing this direct influence on the WEC. In addition, the PTO system directly impacts the capital cost of a project by usually accounting for between 20 to 30 % of the overall cost of capital (Bedard et al., 2004). The reliability of the PTO system also has effects on the energy production, operation and in the maintenance cost. Moreover, research has shown that proper PTO design has an effect on increasing the efficiency and reducing the LCOE of the WEC (Seanergy, 2016). However, unlike the wind energy market, there is no industry standard device for conversion of wave energy and this variety is transferred to the PTO system. There have been studies into many different types of PTO systems, and the type of PTO system used in a WEC is often associated with its size. For instance, the air turbine-based PTO system is normally used in oscillating water column devices and different types of PTO system can be used in point absorber-based devices and it depends on their configuration and may need cascaded conversion mechanisms (Têtu, 2017). There are five types of PTO systems usually used in WECs and among them, the hydraulic motor type PTO system is especially well-suited to absorb energy from high force, slow oscillatory motion and can enable the conversion of reciprocating motion to rotary motion to drive the generator. However, they have various design challenges including efficiency and reliability. The direct mechanical and direct electric drive-based PTO systems provide alternative options, but their technologies are less mature. However, while each PTO system has its advantages and disadvantages, the decisions on which type of PTO system is to be used in a particular WEC depends primarily on the method of capturing the wave power, wave condition, and cost etc. Currently, there is still no PTO system commercially developed and deployed and the design can still be considered to be in the early stages. The research on these PTO systems are ongoing for improving the power conversion efficiencies and getting the best commercial device. Therefore, the wave energy technology is still in the research and development and prototyping phase prior to commercial scale deployment.

By 2019 there are more than 100 wave energy power pilot projects that have been launched, including those projects that have been installed and tested at full scale in the different countries such as USA, UK, Australia, Sweden, Portugal, China, Italy, Norway and others and still numerous number of plans for wave farms to be installed in Australia, France, New Zealand, Sweden, and the UK (Jeffrey and Sedgwick, 2011). There are numerous universities, private companies, organisations, non-profits, and national laboratories that actively support research on wave energy technology in the world.

3.1 University and institute-based research

Currently there are many universities conducting research in the wave energy technology field. Oregon State University, Uppsala University, Plymouth University and the University of Edinburgh are the most famous universities for wave energy technology research. Every year there are more universities joining in the wave energy technology research field and publishing related research articles and creating patents. There are some universities working collaboratively with wave energy developer companies such as Oregon State University worked collaboratively with Columbia Power Technologies and U.S. Navy. They assessed 18 different types of direct-drive technologies, and down-selected to five promising designs (von Jouanne and Brekken, 2011a). Oregon state University and Uppsala University have developed several different prototypes which were deployed in the ocean for testing (Hong et al., 2013; Von Jouanne and Brekken, 2011b). The University of Edinburgh's wave power group proposed the Duck device and EquiMar Project (Drew et al., 2009). Moreover, the wave energy device Supergen 1 and Supergen 2 has been developed by Lancaster University (Drew et al., 2009; McCabe et al., 2006). Some universities from USA, China and Korea have started research on the triboelectric nanogenerator (TENG) based wave energy converter (Khan and Kim, 2016; Liang et al., 2020; Wang et al., 2015). Many research institutes are also involved in wave energy research. Ocean Energy Laboratory of Guangzhou Institute of Energy Conversion (GIEC), Chinese Academy of Sciences, is one of the well-known institutes for wave energy research especially for the Duck device, onshore WEC, OOB (You et al., 2012). Beijing Institute of Nanoenergy and Nanosystems is one of the leading institutes for triboelectric nanogenerator (TENG) based wave energy converter' research and development (Chen et al., 2015). Some leading universities and research institute's names are listed in Table 6 who are well-known for wave energy technologies' research. The University of Western Australia (UWA) also established a Wave Energy Research Centre (OES, 2018a). Moreover, to develop the wave and wind energy technology, The University Adelaide, Australia, and Shanghai Jiao Tong University, China, have established an Australia-China Joint Research Centre of Offshore Wind and Wave Energy Harnessing (OES, 2018a). Moreover, the research centres have been used to test the prototype devices. The OE Buoy was tested at the Hydraulics and Maritime Research Centre (HMRC) in University College Cork, Ireland (OE12, 2020). Hawaii National Marine Renewable Energy Centre (HINMREC) is operated by the Hawaii Natural energy Institute at the University of Hawaii and it helps with the managements of two tests sites in Hawaii, WETS and the OTEC test site (OES, 2018a).

Table 6: Some leading universities and research institute's names

University Name	Country Name	Device or project Name or work type	Reference
The University of Edinburgh	UK	Duck and others	(Drew et al., 2009)
Lancaster University	UK	PS Frog, Supergen 1, 2 and others	(Drew et al., 2009; McCabe et al., 2006)

Oregon state University	USA	Oregon L10	(Waters et al., 2007)
Guangzhou Institute of Energy Conversion (GIEC)	China	Duck, OOB	(You et al., 2012)
Uppsala University	Sweden	Lysekil Project	(Leijon et al., 2008)
Chalmers University	Sweden	Numerical modelling	
University of Stellenbosch	South Africa	SWEC	(Joubert and Van Niekerk, 2009)
Queen’s University of Belfast	Scotland	Isle of Islay	(Falcão and Henriques, 2016)
Saga University	Japan	Caisson OWC	(Khan and Bhuyan, 2009)
Norwegian University of Science and Technology	Norway	CONWEC	(Falnes, 2005)
Ocean University of China	China	Crown	(Liu et al., 2017)
University of Santiago de Compostela	Spain	WaveCat	(Fernandez et al., 2012)
University of Manchester	UK	Manchester Bobber	(MANCHESTER, 2005)
University of Porto	Portugal	CECO	(Rosa-Santos et al., 2019)
University of Genoa	Italy	Seaspoon	(Di Fresco and Traverso, 2014)
University of Lisbon	Portugal	WETFEET and others	(Henriques et al., 2016)
Ghent University	Belgium	LAMWEC	(OES, 2018a)
Aalborg University	Denmark	CNWT	(Windt et al., 2020)
Plymouth University	UK	CNWT, WETFEET and others	(López et al., 2015; Windt et al., 2020)
Maynooth University	Ireland	CNWT	(Windt et al., 2020)
University of Western Australia	Australia	CETO6	(OES, 2018a)
Virginia Tech	USA	Two-body point absorber type WEC	(Martin et al., 2020)
University of Tasmania	Australia	Floating offshore OWC wave energy converter	(Singh et al., 2020)
University of Trento	Italy	U-OWC wave energy converter with dielectric elastomer generator	(Moretti et al., 2020)
Korea Research Institute of Ship & Ocean Engineering (KRISO)	Korea	FPWEC	(OES, 2018a)
Georgia Institute of Technology	USA	Triboelectric Nanogenerator based WEC	(Jiang et al., 2015)
Beijing Institute of Nanoenergy and Nanosystems	China	Triboelectric Nanogenerator based WEC	(Chen et al., 2015)

In addition, many open sea test sites have been launched all over the world and they offer very different facilities to the industry. The advancement of open sea testing services promotes wave energy improvement by allowing practical experience of installation, operation, maintenance and decommissioning activities for prototypes and farms, including services and streamlining procedures. Some of the leading open sea test sites have been shown in Table 7.

Table 7: Open Sea test sites around the world

Test Site Name	Location
Wave Energy Research Centre (WERC)	Lord's Cove, Newfoundland & Labrador, Canada
European Marine Energy Centre (EMEC)	EMEC Orkney, Scotland
Wave Hub	Wave Hub Cornwall, England
U.S. Navy Wave Energy Test Site	Kaneohe Bay, USA
Pacific Marine Energy Center PacWave North Site	Newport, Oregon, USA
Center for Ocean Renewable Energy	Durham, New Hampshire, USA
UMaine Deepwater Offshore Renewable Energy Test Site	Monhegan Island, Maine, USA
Mutriku Wave Power Plant	Basque Country, Spain
BiMEP	Basque Country, Spain
OTEC Test Site	Keahole Point, HI, USA
Oceanic Platform of the Canary Islands (PLOCAN)	Canary Islands, Spain
Aguçadora test site	Aguçadora, Portugal
Pilot Zone	Viana do Castelo, Portugal
DanWEC	Hanstholm, Denmark
DanWEC NB	Nissum Bredning, Denmark
The Lysekil wave energy research test site	Lysekil, Sweden
Söderfors research site	Dalälven, Sweden
Ostend wave energy test site	Harbour of Ostend, Belgium
Runde Environmental Centre (REC)	Runde Island, Norway
Wanshan wave energy full scale test site	Wanshan, Guangdong Province, China
SEM-REV, wave and floating offshore wind test-site	Le Croisic, France
K-WETEC (Korea Wave Energy Test and Evaluation Centre)	Jeju, Republic of Korea

3.2 Commercial Operations

Currently, there are many companies working worldwide in the wave energy field and they have developed many wave energy devices. The European Marine Energy Centre (EMEC) website (last updated: 5th September 2019) provides a comprehensive list of companies worldwide (EMEC, 2019). Most wave energy developer companies have come from the European and USA regions. There are very few companies that are active in Asian or South American countries. Even though the development of wave energy technology is still controlled by start-up companies, large engineering firms and utilities have also come into the market. In some countries several companies are working together to develop the wave energy technology. The Danish Wave Energy Partnership has included 11 active Danish developer companies and they are working together for the advancement of wave energy by industrial partnerships (OES, 2018a). The largest number of wave developer companies are private companies and government fund award winning companies. There are many existing wave energy companies that have shut down because of financial conditions and bankruptcies. Therefore, government investment for wave energy is very important for wave energy research and development. The well-known Pelamis wave energy converter project closed because of Bankruptcy (November 2014) after 12 years of intensive development (WAVE.CA, 2020). The wavebob and Langlee wave energy projects closed as well in 2013 and 2016, respectively. Another recently closed wave energy project is the seabased wave energy project which closed in 2019 (WAVE.CA, 2020). Some companies have been working over a long time in wave energy research field like Ocean Power Technologies (OPT), Columbia Power Technologies, Ocean Wave Energy Company, and Carnegie Wave Energy Limited and still their proposed devices are in the research and development (R&D) mode.

3.3 Networking for Wave Energy Technology

Currently, the WEC research is at a significant stage in its advancement, facing several challenges that need research to re-focus on a universal techno-economic viewpoint, where the economy considers the technology's full life-cycle costs. It also needs the improvement of WECs appropriate for niche markets as there are imbalances in the world with respect to wave energy resources, companies, national programmes and investments. By reducing technological or nontechnological risks, this sector can also increase the confidence of the potential investors. By including engineers, environmental scientists, economists, lawyers, regulators and policy experts, this can be done via interdisciplinary methods. The future development of wave energy technology requires requisite care relative to other more mature and commercial technologies (e.g. offshore wind, solar energy).

Significantly, there are several organisations that have been established to collaborate worldwide with wave energy developers and governments. Ocean Energy Europe (OEE), a not-for-profit organisation, is the largest network in the world of ocean energy professionals and it has collaboration with 120 organisations, including Europe's top utilities, industrialists and research institutes (Europe, 2020a). Each euro invested in OEE is used to help the European ocean energy industry. The Ocean Energy Systems Technology Collaboration Programme (OES), working based on a framework decided by the International Energy Agency (IEA), is an international organisation that is actively collaborating between countries with the aim of advancing ocean energy research, development and demonstration of technologies to generate electricity from ocean energy resources (all forms of renewable energy) by international co-operation and information exchange (OES, 2020a). OES was established by Denmark, UK and Portugal in 2001 and has increased to its current twenty-five members where Australia is the last joining country (May 2018). The primary education and research initiatives of OES are aimed at promoting the feasibility, recognition and adoption of ocean energy systems in an environmentally acceptable manner. The OES's wave energy modelling group is working in a project with several objectives which are; to assess the accuracy and establish confidence in the use of numerical models, to validate a range of existing computational modelling tools, identify simulation methodologies for reducing the risk in technologies development, uncertainty in LCOE models and for improving the energy capture ability and loads, and future research and development needed to improve the computational tools and methods. To achieve those objectives the wave energy modelling group deployed several phases of wave energy converters for testing, starting in 2018 (OES, 2018a).

The European Marine Energy Centre (EMEC) Ltd, established in 2003, was the world first and only centre to give developer companies, wave and tidal energy converter-technology developers, that generate electricity from ocean energy resources, certified open-sea testing services (EMEC, 2020a). The mission of EMEC is to decrease the time, cost, and risk related with marine energy technology development, increasing the use of EMEC's modified facilities as well as industry knowledge and other experiences. EMEC have 13 grid connected test berths and many marine energy converters have been installed, more than at any other single global test site. EMEC is an independent organisation which has unique position in the world to maintain relations with various developer companies, academic organizations and governing bodies and presently working with companies and researchers to broaden research programme to solve a variety of environmental and operational challenges relevant to industry (EMEC, 2020b).

An open pan European Network for marine renewable energy (WECANet) with focus on wave energy was launched in 2018, founded by Ghent University, to assist networking, training and collaboration in Europe (Stratigaki, 2019). The aims of the WECANet is to create a strong platform for networking and collaboration in wave energy which will create space for dialogue between all stakeholders. At present, there are 31 partner countries active in the network and among them 30 countries are from Europe in addition to the USA. The WECAnet focuses on all important topics concerning the subjects of wave energy technology and it has 4 working groups (WG). The working group 1 (WG1) focuses on Numerical hydrodynamic modelling for WECs whereas the WG2 considers experimental hydrodynamic modelling for WECs including PTO systems. WG3 is concerned with technology development with the goal of having a better understanding of the techno-economic features of wave energy technology. WG4 focuses on the impacts and economics of wave energy and their effect on decision and policy making.

There is another well-known Network OCEANERA-NET working in the EU for ocean energy research and innovation programmes (ERA-NET, 2020). OCEANERA-NET have a Network of 15 national and regional funders and managers and among them 8 countries are from the EU. The goal of OCEANERA-NET is to organize funding programmes to support research and innovation between European countries and regions in the ocean energy sector. However, there are many organisations arranging conferences that focus on the industrial advancement of ocean energy including the European Wave and Tidal Energy Conference (EWTEC) series, Asian Wave and Tidal Energy conference (AWTEC) and the International Conference on Ocean Energy (ICOE).

3.4 Current WEC Research status and future research

There are numerous research and development (R&D) project works ae going on all over the world focusing on future wave energy technologies and prototype developments. Some current research WEC projects have been listed in Table 8. In the last decade's research and development work of WEC, the numerical modelling has achieved the desired level of maturity to model multi-body interactions to the second order or higher accuracy, such as non-linear BEM, CFD (Stratigaki, 2019). A wide variety of models are presently available, ranging from the simplest ones which can simulate wave propagation and far-field effects to the more complex models that can deal with the actual interaction between the waves and the devices.

Table 8: Some Current WEC research projects

Project Name	**Country Name**	**Present Status**	**Ref.**
CorPower Ocean	Sweden	*Stage 4- Demonstration and prototype certification of single device full scale C4 WEC. *The overall aim is to allow successful introduction onto the market of approved and warrantied WEC devices by end of 2023-2024.	(ocean, 2020b)
Bombora	UK	Working on the financial arrangements for first commercial array 1.5MW WEC device project.	(Bombora, 2020)
Carnegie	Australia	*Now moving with the design of CETO 6 wave energy device of 1 MW *The 1 MW CETO6 device will be expanded to 15 MW by 2021 for UK	(Magagna et al., 2016)
Penguin	Scotland	*In 2019 the WEC2 (commercially ready device) deployed in EMEC's grid connected wave test site in Orkney	(OES, 2018a)

		* It is aiming to increase the speed of wave power production, decreases the LCOE and create an efficient supply chain	
LAMWEC (Laminaria)	UK	In operation at EMEC's Billia Croo site.	(LAMINARIA, 2020)
Direct drive WEC (Columbia Power Technologies)	USA	Permanent-magnet 500 kW generator is in operation.	(OES, 2018a)
StingRAY (Columbia Power Technologies)	USA	Started fabrication of the device.	(OES, 2018a)
Ocean Energy OE35 Buoy	Ireland	Deployed in Hawaii at the US Navy's Wave Energy Test Site (WETS).	(OES, 2018b)
WavePiston	Denmark	Started continuing testing at DanWEC Hanstholm in 2019. Aim to have the first commercial project by 2022.	(WavePiston, 2020)
ResenWaves	Denmark	Started test in Nissum Bredning in 2019.	(OES, 2018b)
SINN Power GmbH	Germany	*Final module prototype has been installed in autumn 2019. *Want to build and test the first floating WEC array with 21 modules with an overall capacity of 0.75 MW and approximately 1 km away from the coast.	(SINNPOWER, 2020)
Waveroller	Portugal	Under development and in the delivery phase.	(Waveroller, 2020)
OPERA Project	Spain	In operation and trying to reduce wave energy cost.	(OES, 2018b)

More advanced models can also simulate the mooring system, the existence of articulated parts connected by hinges, springs and pulleys and their use will help properly investigate the behaviour of the PTO system. The models require a correct understanding of the governing physics to optimize the WEC's design phase and evaluate its survival, covering different time and space scales.

Recently, numerical modelling researchers from several universities (Oregon State University, Georgia Tech, University of Prince Edward Island, Carnegie Mellon University, University of California at Berkeley and Virginia Tech) jointly developed simulation software, an open-source WEC simulation tool, known as WEC-Sim (Wave Energy Converter SIMulator) (Energy, 2015). The code of the WEC-Sim has been created in MATLAB/SIMULINK by using the multi-body dynamics solver Simscape Multibody and the WEC-Sim could model devices that contain rigid bodies, power-take-off systems, and mooring systems. The Waterpower Technologies Office from the U.S. Department of Energy provided funding for the WEC-Sim project and the effort for developing the code was a collaboration between the Sandia National Laboratories (Sandia) and National Renewable Energy Laboratory (NREL).

However, compare with other renewable energy technologies, the costs of the wave energy technologies are too high, and this is one of the biggest challenges for commercializing WEC devices (Contestabile et al., 2017). To commercialize WEC devices in large scale there are a number of improvements that are required such as the important challenges of WEC PTO system reliability, maintenance, survivability, efficiency which need to be solved. Furthermore, losses in the energy-conversion chain should be decreased (Liang et al., 2017; Liu, 2016). Moreover, the peak-to-average power ratio control (peak shaving), service life of mooring lines, power cables etc. of the WEC should be improved and the problems associated with fatigue and ocean biofouling should be solved (Henriques et al., 2016; Yang et al., 2017).

Obtaining specific and steady wave climate data is one of the key activities in the wave energy resource assessment and this can be solved by numerical modelling using consistent data supplied from buoys, coastal stations, research ships or satellites (Rusu and Onea, 2017).

Ocean Energy Systems (OES) projected the Levelised cost of energy (LCOE) analyses, as shown in Figure 20, for wave energy in 2015 which showed that the cost should be reduced significantly by 2050 (Seanergy, 2016). Still the object of the wave energy technology roadmap initiated by OES is to achieve these LCOE targets (OES, 2018a). Moreover, it is hoped that the hybrid systems (combined wave and offshore wind energy) can further reduce the LCOE (Pérez-Collazo et al., 2015). If the wave energy converter devices are installed in the offshore wind turbine structure then the installation, foundation and mooring costs will be reduced. It is expected that developments in the future generation of wave energy technology could reduce the costs of power take-off (by 22%), installation (18%), operation and maintenance (17%), foundation and mooring (6%) and grid connection (5%) (IRENA, 2014).

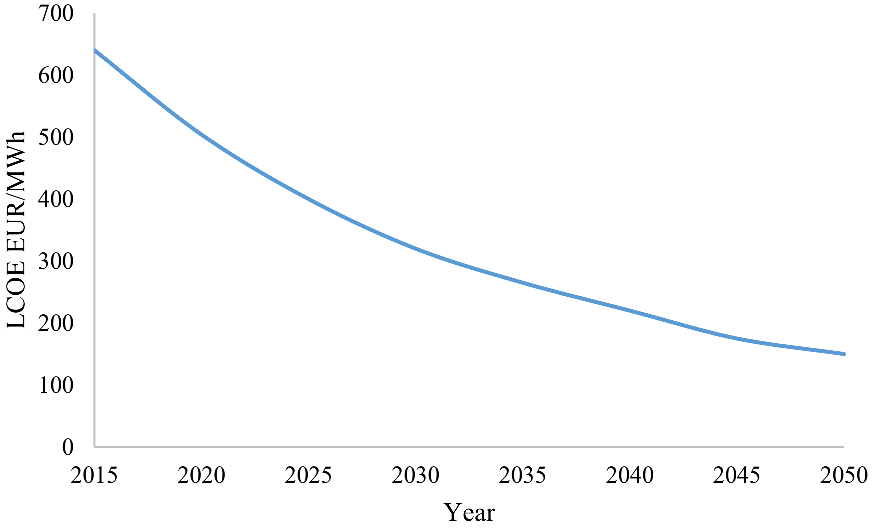

Figure 20: LCOE projections for ocean wave energies (Seanergy, 2016)

4. Current Market of WEC

The size of the potential ocean energy market is huge. By 2050, it is projected that more than 300 GW of ocean energy installed capacity could have been deployed, capable of generating 68K direct jobs and saving 500 million tonnes of CO2 emissions (OES, 2020b). The ocean energy industry is preparing to install 100 GW of production capacity in Europe alone by 2050, meeting 10 percent of demand for electricity which would be enough to meet the daily needs of 76 million households, creating 40K skilled jobs in Europe (Europe, 2020c). European companies are today the strong global leaders in ocean energy, accounting for 66 percent of tidal energy patents and 44 percent of wave energy patents worldwide (Europe, 2020b). By using the European technology, significant projects have been developed outside Europe in Canada and South-East Asia. Therefore, EU companies are in a strong position to lead the global market as seen in the analysis in Table 9. However, most of the wave energy technologies are still at an early stage and only a few companies have been able to test their devices in the open sea (Lasa et al., 2012).

Table 9: Country based leading Wave energy developer companies in the world

Country	**Company**	**Project/Device type**	**PTO system**
Australia	Carnegie Wave Energy Limited https://www.carnegiece.com/	CETO 5 and 6	Hydro turbine transfer system
	Bombora Wave Power (https://www.bomborawave.com/)	mWave	Pneumatic air turbine transfer system
	WaveRider Energy http://www.waveriderenergy.com.au/	Wave Rider	Direct mechanical drive system
	BioPower Systems Pty Ltd (http://bps.energy/)	bioWAVE	Hydraulic motor system
	Wave Swell Energy https://waveswellenergy.com.au	King Island Project	Pneumatic air turbine transfer system
Belgium	Laminaria http://www.laminaria.be/technology.html	LAMWEC	Direct mechanical drive system
Brazil	Coppe Subsea Technology http://www.lts.coppe.ufrj.br/2017/	Clean Energy from Waves	Hydro turbine transfer system
Canada	Neptunewave https://www.neptunewave.ca/	Neptune 5	Direct mechanical drive system
	Accumulated Ocean Energy (AOE) (https://www.aoecanada.ca/)	pWEC, pROWS	Pneumatic air turbine transfer system
Chile	WILEFKO http://www.wilefko.com/web/en/	Wilefko WEC	Pneumatic air turbine transfer system
Cyprus	Sea Wave Energy Limited (SWEL) https://www.swel.eu	Waveline Magnet 9.1 (WM9.1)	Hydraulic motor system
Denmark	Resen Energy http://www.resenwaves.com/	Resen Waves LOPF buoys	Direct mechanical drive system
	WavePlane Production http://www.waveplane.com/	WavePlane	Hydro turbine transfer system
	WavePiston https://www.wavepiston.dk/	WavePiston	Hydro turbine transfer system
	Crestwing https://crestwing.dk/	Crestwing	Direct mechanical drive system
	Weptos http://www.weptos.com/	WEPTOS WEC	Direct mechanical drive system
	Leancon Wave Energy http://www.leancon.com/	LEANCON WEC	Pneumatic air turbine transfer system
	Floating Power Plant http://www.floatingpowerplant.com/	Poseidon – Wave wind hybrid	Hydraulic motor system
	Wave Star Energy ApS http://wavestarenergy.com/	Wave Star	Hydro turbine transfer system
	Wave Dragon http://www.wavedragon.co.uk/	Wave Dragon	Hydro turbine transfer system
	KN Ocean Energy Science & Development https://wavepartnership.dk/knswing-2012	KNSWING	Pneumatic air turbine transfer system

Finland	AW Energy https://aw-energy.com/	WaveRoller	Hydraulic motor system
	Wello OY https://wello.eu/	Penguin	Direct mechanical drive system
France	Hydrocap Energy SAS https://hydrocap.com/	Seacap	Hydraulic motor system
	Ecole Centrale de Nantes https://www.ec-nantes.fr/	SEAREV	Hydraulic motor system
Germany	NEMOS GmbH https://www.nemos.org/	NEMOS	Direct mechanical drive system
	Sinn Power https://www.sinnpower.com/	Sinn Power WEC	Direct electrical drive system
	Brandl Motor http://brandlmotor.de/wellenenergie_eng.htm	Brandl Generator	Direct electrical drive system
Hong Kong	Finima-Aimmer (https://www.finima.co/)	Aimmer III	Other
Ireland	Blue Power Energy Ltd http://bluepowerenergy.ie/	Blue Power Take Off (PTOU)	Direct mechanical drive system
	Sea Energies Ltd http://seaenergies.com/	SEWEC	Pneumatic air turbine transfer system
	Joules Energy Efficiency Services Ltd https://www.jouleswavepower.com/	Wave Train, TETRON	Hydro turbine transfer system
	Ocean Energy Ltd http://www.oceanenergy.ie/	OEBuoy	Pneumatic air turbine transfer system
	Cyan Technology Ltd https://cyanconnode.com/	CyanWave4	Hydraulic motor system
	Limerick Wave Ltd https://limerickwave.emergemediaireland.com/	Limerick Wave PTO	Direct mechanical drive system
	Jospa Ltd https://jospa.ie/	Irish Tube Compressor	Pneumatic air turbine transfer system
	Sea Power Ltd http://www.seapower.ie/	Sea Power Platform	Hydraulic motor system and Direct mechanical drive system
Israel	Eco Wave Power https://www.ecowavepower.com/	Wave Clapper, Power Wing	Hydraulic motor system
Italy	Waves for Energy http://www.waveforenergy.com/tech/iswec	ISWEC	Direct mechanical drive system
Netherlands	Slow Mill http://www.slowmill.nl/	Slow Mill	Direct mechanical drive system
	SBM Offshore https://www.sbmoffshore.com/	S3	Other
Norway	Intentium AS http://www.intentium.com/index.html	Intentium Offshore Wave Energy Convertor	Hydro turbine transfer system
	Aker Solutions ASA https://akersolutions.com/	Aker WE	Direct mechanical drive system
	Pontoon Power https://www.pontoon.no/	Pontoon Power Converter	Hydro turbine transfer system

	Pelagic Power AS http://www.pelagicpower.no/	W2Power hybrid	Hydro turbine transfer system
	Bolt Sea Power https://boltseapower.com/	Bolt Lifesaver	Direct mechanical drive system
	Havkraft http://www.havkraft.no/	Havkraft Wave Energy Converter (H-WEC)	Other
	Langlee Wave Power http://www.langleewp.com/	Langlee System	Direct mechanical drive system
Russia	Applied Technologies Company, Ltd (ATC) http://atecom.ru/	Float Wave Electric Power Station (FWEPS)	Direct electrical drive system
Singapore	Hann-Ocean's (http://www.hann-ocean.com/)	Drakoo	Hydro turbine transfer system
Slovenia	Sigma Energy http://www.sigma-energy.si/	Sigma WEC	Direct mechanical drive system
South Korea	Ingine Inc (http://www.ingine.co.kr/en/)	INWave	Direct mechanical drive system
Spain	Rotary Wave SL http://www.rotarywave.com/	Rotary, Butterfly device	Other
	Opera http://opera-h2020.eu/	MARMOK-A-5	Pneumatic air turbine transfer system
	Norvento https://www.norvento.com/en/	Wavecat	Hydro turbine transfer system
Sweden	Ocean Harvesting Technologies https://www.oceanharvesting.com/	InfinityWEC	Direct mechanical drive system
	CorPower Ocean AB http://www.corpowerocean.com/	Corpower wave energy converter	Direct mechanical drive system
	Waves4Power AB (https://www.waves4power.com/)	WaveEL-buoy	Hydro turbine transfer system
	Vigor Wave Energy AB http://vigorwaveenergy.com/	Vigor Wave Energy Convertor	Hydro turbine transfer system
	Seabased AB (https://www.seabased.com/)	Linear generator (Islandberg Project)	Direct electrical drive system
	Sea Power International AB http://www.seapower.se/	Stream turbine	Hydro turbine transfer system
Taiwan	Aquanet power (https://www.aquanetpower.com/)	aquaWave	Pneumatic air turbine transfer system
UK	Snapper Consortium http://www.snapperfp7.eu/home	Snapper	Direct mechanical drive system
	Trident Energy Ltd https://www.trident-energy.com/	PowerPod & PowerPod II	Direct electrical drive system
	Fred Olsen Ltd https://www.fredolsen.co.uk/	Lifesaver	Direct mechanical drive system
	Caley Ocean Systems https://caley.co.uk/	Wave Plane	Other
	Albatern Ltd http://albatern.co.uk/	WaveNet, SQUID	Hydraulic motor system

	Marine Power Systems http://marinepowersystems.co.uk/	WaveSub	Other
	Checkmate Seaenergy UK Ltd https://www.checkmateukseaenergy.com/	Anaconda	Hydro turbine transfer system
	AWS Ocean Energy http://www.awsocean.com/	AWS-III	Direct mechanical drive system
	WITT ENERGY (https://www.witt-energy.com/index.html)	Witt	Direct mechanical drive system
	Ecotricity https://www.ecotricity.co.uk/	Searaser	Hydraulic ram
	wave-tricity https://wave-tricity.com/	(---)	Other
	Polygen Ltd http://www.polygenlimited.com/	Ocean WaveFlex and Volta WaveFlex	Hydraulic motor system
USA	Oscilla Power, Inc https://oscillapower.com/	Triton WEC	Direct mechanical drive system
	OWEC Ocean Wave Energy Company https://www.owec.com/	OWEC (Ocean Wave Energy Converter)	Direct electrical drive system
	Resolute Marine Energy Inc https://www.resolutemarine.com/	SurgeWEC	Other
	Npowerpeg https://npowerpeg.com/	nPower WEC	Direct electrical drive system
	Spindrift Energy http://www.spindriftenergy.com/	Spindrift Energy Device	Hydro turbine transfer system
	SARA Inc https://sara.com/	MHD Wave Energy Conversion (MWEC)	Direct electrical drive system
	M3 Wave LLC https://www.m3wave.com/	DMP Device	Pneumatic air turbine transfer system
	Marine Energy Corporation http://www.marineenergycorp.com/	Wave Catcher	Direct mechanical drive system
	SeaDog Systems, Inc. http://www.inri.us/	SEADOG	Hydro turbine transfer system
	Brimes Energy http://www.brimesenergy.com/	Jellyfish	Direct mechanical drive system
	Float Inc http://www.floatinc.com/Default.aspx	Rho-Cee	Pneumatic air turbine transfer system
	Energystics http://vibristor.com/	Vibristor	Direct electrical drive system
	Aqua-Magnetics Inc http://www.amioceanpower.com/home.html	Electric Buoy	Direct electrical drive system
	Ecomerit Technologies http://www.ecomerittech.com/	Centipod	Hydro turbine transfer system
	Calwave http://calwave.energy/	Calwave, WaveCarpet	Hydraulic motor system
	ELGEN Wave http://www.elgenwave.com/	Horizon Platform	Direct mechanical drive system

	AeroVironment Inc https://www.avinc.com/	Eel Grass	Hydro turbine transfer system
	Able Technologies LLC http://www.abletechnologiesllc.com/	Electric Generating Wave Pipe	Direct mechanical drive system
	Atargis Energy Corporation https://atargis.com/	CycWEC	Direct mechanical drive system
	Atmocean Inc https://atmocean.com/	WES - Wave Energy System	Hydraulic motor system
	Columbia Power Technologies https://columbiapwr.com/	StingRAY	Direct electrical drive system
	Ocean Energy Industries Inc https://oceanenergyindustries.com/	WaveSurfer	Direct mechanical drive system
	Ocean Power Technologies (OPT) https://www.oceanpowertechnologies.com/	Power Buoy	Hydro turbine transfer system

It can be seen from Table 9 that there are numerous developer companies actively working around the world. It is also clear that the largest number of developers are from Europe (63%) and North America (25%). Moreover, different developers are using different types of PTO systems. Figure 21 presents the analysis of the number of developers using the various PTO systems based on Table 9.0.

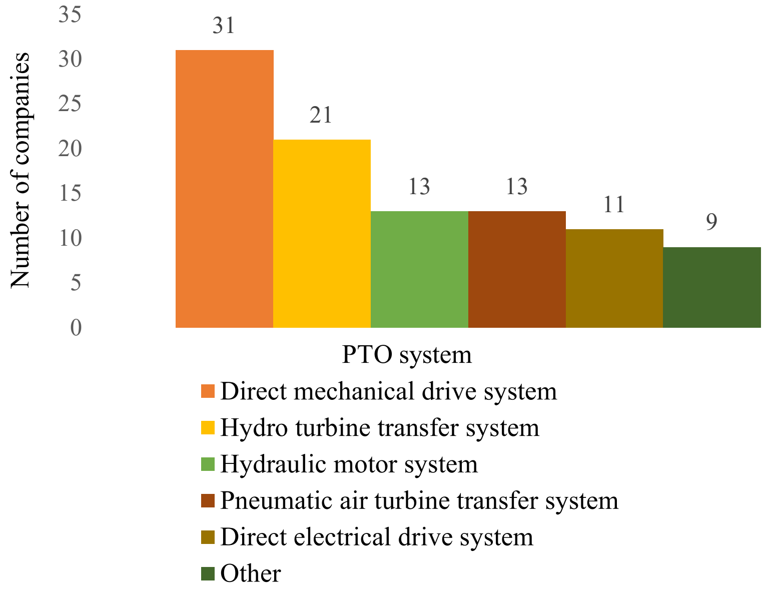

Figure 21: Active companies with different types of PTO systems

Figure 21 shows that 31 developers throughout the world are actively working to utilize the direct mechanical drive system based PTO whereas the second most popular PTO system is the hydro-turbine transfer which is currently used by 21 developers. There are the same number of companies (13) using hydraulic motor & pneumatic air turbine transfer systems on their respective WEC devices and 11 developers are working with direct electrical drive systems to convert wave energy into electrical energy.

5. Conclusion and remarks

As studied in this paper, wave energy technologies are currently undergoing innovative research and development all over the world. Due to the significant potential of the future ocean energy resources, the improvement and progress of wave energy technologies continues to develop very fast. Most of the reported research works have been done in Europe and the current leading wave energy technology developer companies also come from either Europe or the USA. The analysis has shown that importantly there are many research and development works in different universities and research institutes, and in unique networks of organisations with wave energy developers and governments.

This paper has presented a brief review of the advances in power take-off systems for wave energy technologies. The novel analysis has shown that power take off systems can be classified into their five major groupings of direct mechanical drive, hydro and air turbine transfer system, hydraulic motor system, direct electrical drive system, along with other triboelectric nanogenerators. The hydraulic motor, turbine transfer and direct mechanical drive systems are the most popular used PTO systems in the prototype WEC because of technology maturity and their effective working ability. So far, most of the prototype WECs have been deployed in offshore locations because of the higher wave power density and the onshore land installation issues. The analysis of the major advances and challenges of these systems has also been provided.

The important research emphasis on numerical modelling and simulation of prototype devices has been seen as very important for improving device efficiency, survivability and for reducing maintenance costs. Ongoing issues of modelling PTO devices using detail from intended operating location, water depth and sea state continue to be needed for improving the operational life while reducing costs.

Research into hybridization with other sources of renewable energy in the ocean environment has been noted as another important topic for improving the future economic viability of wave energy systems.

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