REVIEW ARTICLE

Technology Prospects of Wave Power Systems

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ABSTRACT In this work, a comparative overview of wave power technologies is carried out. Although wave energy resource is theoretically enormous, it is only located in certain areas of the globe where sufficiently high wave power potential exists. These areas are the western seaboard of Europe, the northern coast of the UK and the pacific coastlines of North and South America, Southern Africa, Australia and New Zealand. In addition, the highest potential exists in deep ocean waters, many kilometers offshore. Therefore, only a fraction of the wave energy resource can be harnessed by current wave energy technologies. Currently, wave power technologies are neither mature nor have become widely commercialized. Although these technologies can cover onshore, near-shore and offshore applications, the vast majority of wave energy devices developed today from these technologies is still in prototype demonstration stage. It is, therefore, too early to predict which of these technologies will become the most prevalent one for future commercialization. Currently the major obstacles towards wave energy commercialization are the high capital costs of wave energy devices (translated into high electricity unit costs for power generation) and the adverse working weather conditions that these devices have to endure, requiring additional safety features which results in escalation of the capital costs. With the future commercialisation of the wave power systems the operating costs are expected to reduce leading towards the competitiveness of this technology.

KEYWORDS wave energy, wave to electricity, renewable energy sources.

Introduction

Currently, global concerns on environmental protection and sustainable development have resulted in a critical need for cleaner energy generation technologies. Such technologies offer the promise of mitigating harmful greenhouse gases emissions in the atmosphere, global warming and of reducing global dependence on fossil fuels for energy production. However, it is evident by current scenarios and projections up to year 2030, that there will be a continuous increase in worldwide energy demand. Consequently, unless specific policy initiatives and measures are undertaken, global greenhouse gas emissions will continue to rise significantly causing severe environmental destruction and climate change effects.

Many countries have already focused their energy strategy towards achieving maximum greenhouse gas reductions from power generation plants. This new strategy is expected to lead to the acceleration in the development of renewable energy sources for electricity generation (RES-E). Already, RES-E have been successfully integrated into the global electricity networks and constitute an important factor in the global energy mix, contributing to about 18% of total world electricity requirements. The most widely used RES-E today are the hydroelectric, biomass, wind, geothermal and solar technologies.

An emerging RES-E technology, which is currently under significant research and development, is wave energy. Wave energy is essentially an indirect form of solar energy since waves are formed by the movement of winds, which, in turn, are essentially generated by the differential solar heating of the earth. Waves are generated over large areas of ocean and, once generated, travel immense distances with only small energy losses. Waves effectively average out the wind that generates them over large areas which results in a high level of consistency compared to wind or solar energies [Stoutenburg, Jenkins, and Jacobson, 2010]. Oceans, which form the backbone of wave energy, cover 75% of the world surface and therefore hold significant wave energy resource that could be exploited to contribute in a sustainable manner to meeting the increasing global electrical energy demand. It is estimated that the wave energy resource of 2000 TWh that could be harvested annually from the world's oceans is more than the current total amount of global demand for electricity.

The idea of converting the energy of ocean surface waves into useful energy forms is not new. There are techniques that were first patented as early as 1799 [Clément et al., 2002]. The intensive research and development study of wave energy conversion began, however, after the dramatic increase in oil prices in 1973. Different countries with exploitable wave power resources considered wave energy as a possible source of power supply and introduced support measures and related programmes for wave energy. Several research programs with government and private support started at that time, aiming at developing industrially exploitable wave power conversion technologies in the medium and long term.

Recently, the electric power generation of co-located offshore wind turbines and wave energy converters along the California coast was investigated in [Stoutenburg et al., 2010]. The results indicated that co-located offshore wind and wave energy farms generate less variable power output than a wind or wave farm operating alone. Also, the different power output profile from both technologies allows for a reduction in the required capacity of the offshore transmission system. Thus, economic benefits of combining wind and wave power to reduce intermittency exists by the reduction of the associated transmission costs [Stoutenburg and Jacobson, 2011].

In this work, a comparative overview of wave power technologies is carried out. In section 2, the wave energy basic theory and the wave energy potential are presented. In section 3, the current wave energy utilization technologies are described along with the existing major demonstration plants of each technology around the world today. In section 4, the principles and the infrastructure of wave to electrical energy conversion are described and in section 5, the economics of wave energy devices are discussed. The conclusions are summarized in section 6.

Fundamentals of wave energy

Wave power is the transport of energy by ocean surface waves, and the capture of that energy to do useful work such as power generation, water desalination, or the pumping of water. However, wave power generation is not currently a widely employed commercial technology, although, there have been attempts at using it since 1890. In many areas of the world, the wind blows with enough consistency and force to provide continuous waves, leading to a large potential energy in the ocean waves. Wave power devices extract energy directly from the surface motion of ocean waves or from pressure fluctuations below the surface. The wave power potential however, varies considerably in different parts of the world, and therefore wave energy can't be harnessed effectively everywhere.

Aspects of wave energy in deep or shallow water

Generally, in the case of linear plane waves in deep water, particles on or near the surface move in circular paths in oscillatory motions, through a combination of longitudinal, back and forth, and transverse, up and down wave motions. When waves propagate in shallow water, where the depth is less than half the wavelength, λ, the particle trajectories are compressed into ellipses [Nihoul, 1981], as shown in Fig. 1. These oscillatory motions of a particle near or on the surface due to wave movement can provide energy transfer via pressure fluctuations

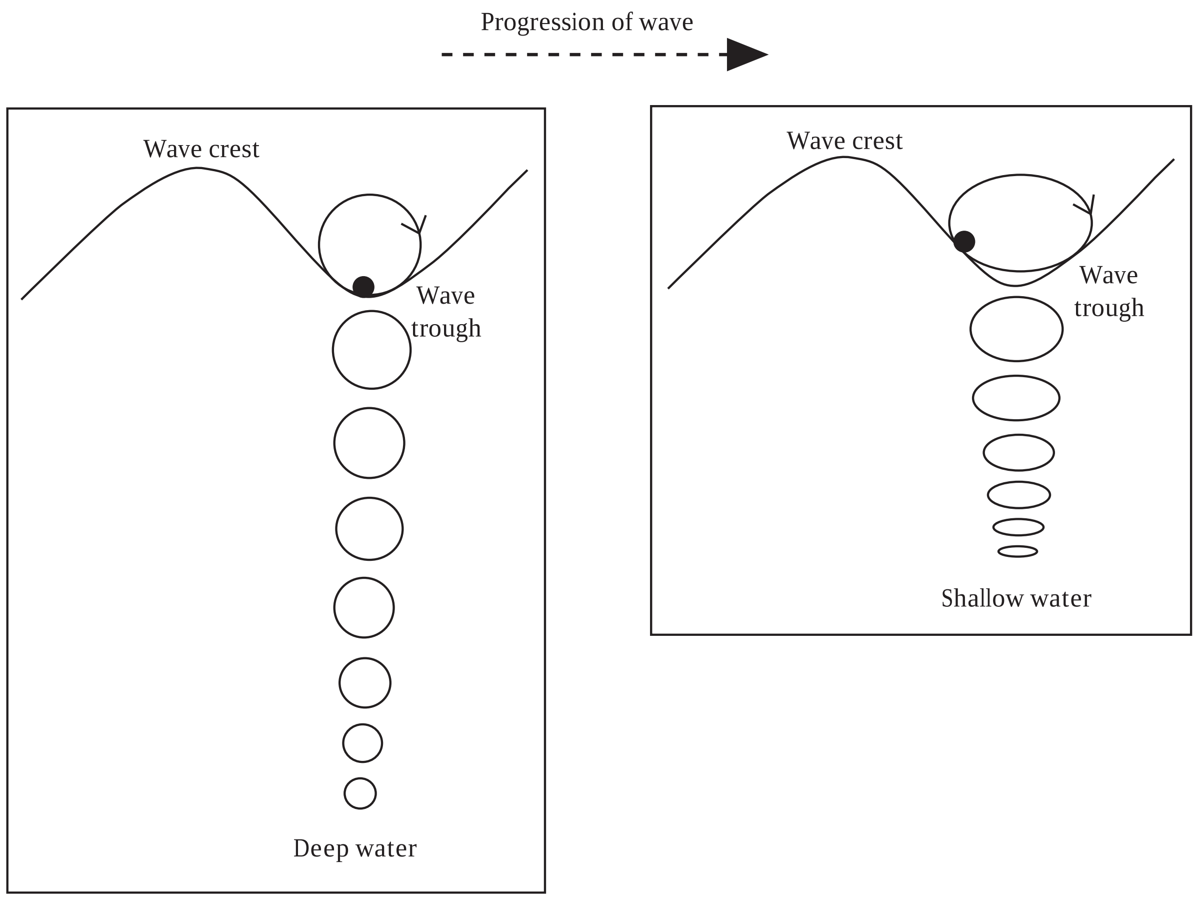

Figure 1 A particle motion in a wave, at deep or shallow water

The oscillatory motions are highest at the surface and diminish exponentially with depth. As shown in Fig. 1, in deep water, as the depth below the free surface increases, the radius of the circular motion decreases. At a depth equal to half the wavelength, *ë*, the orbital movement has decreases to less than 5% of its value at the surface. In the same way, in shallow water, as the depth below the surface increase, the radius of the elliptical motion decreases and therefore the elliptical movement flattens significantly. Therefore, the pressure fluctuations at greater depth are too small to be interesting from the point of view of wave power and this is why any wave power device or converter to exploit pressure fluctuations has to be located at the surface. In addition, the regularity of deep water ocean swells, where predictable long wavelength oscillations are typically seen, offers the opportunity for the development of energy harvesting technologies that are potentially less subject to physical damage by near shore cresting waves [Adee, 2009].

Wave energy potential

Ocean waves represent a form of RES-E created by wind currents passing over open water. Capturing the energy of ocean waves in deep offshore locations has been demonstrated as technically feasible. Compared with other forms of offshore RES-E, such as photovoltaic, wind, or ocean current, wave energy is more continuous but highly variable, although wave levels at a given location can be confidently predicted several days in advance. Because wind is generated by uneven solar heating, wave energy can be considered a concentrated form of solar energy. Incoming solar radiation levels that are on the order of $100W/m^2$ are transferred into waves with power levels that can exceed 1000kW/m of wave crest length [US Department of the Interior, 2006].

It is estimated that global wave power resources are enormous, and could generate between 1 TW and 10 TW of power. The bulk of this huge wave resource is generated in the midst of the earth's oceans due to the presence of storm winds. Although these storm winds generally create irregular and complex waves, in deep water and after the storm winds die down, the storm waves can travel thousands of kilometers in the form of regular smooth waves, or swells that retain much of the energy of the original storm waves. The energy in swells or waves dissipates after it reaches waters that are less than approximately 200 m deep. At 20 m water depths, the wave's energy typically drops to about one-third of the level it had in deep water. However, currently it is not practical to obtain wave power from deep water due to the associated transmission costs.

Therefore, while most of the wave power resource is located in deep ocean waters, it is neither practical nor possible to be entirely captured [CRES, 2002]. In reality, only about 0.5 TW of wave power can actually be harnessed with the currently available technologies, since wave energy can be effectively captured in close proximity to the shore or on the shoreline and not in the oceans where waves are typically 2-3 times more powerful.

The main disadvantage of wave power is its largely random variability in several time-scales such as from wave to wave, with sea state and from month to month, although patterns of seasonal variation can be recognized in practice. Typically, wave behavior is easier to predict in deep water than in shallow water. In some cases, ocean waves caused by winds can be very predictable, being able to be predicted five days in advance. Studies aiming at the characterization of the wave energy resource have resulted in the production of basic and valuable tools for wave energy planning, such as the WERATLAS. The, European Wave Energy Atlas (WERATLAS) uses high-quality results from numerical wind-wave modeling, validated by wave measurements where available and contains detailed wave-climate and wave energy statistics at 85 points off the Atlantic and Mediterranean coasts of Europe. These data concern locations in the open sea, at distances from the coast of a few hundred km [Falcão, 2010].

As waves propagate into the shore, and the water becomes shallower, waves are modified in a complex way by bottom effects such as refraction, diffraction, bottom friction and wave breaking and by sheltering due to the presence of land e.g., headlands and islands. As a result, the waves become more unstable and unpredictable, higher and steeper, ultimately assuming the sharp-crested wave shape. For these reasons, the wave energy resource characterization in shallow waters, defined as waters with less than 50 m water depth, has been done only for specific sites where plants are planned to be deployed. An exception is the ONDATLAS [Falcão, 2010], a detailed near-shore wave energy atlas for Portugal, whose 500 km long western coast is relatively straight, the bottom profile exhibiting little change over long coastal stretches.

Due to a wide annual and seasonal variation in wave power, the actual global wave energy potential cannot be reflected with a single measurement value. However, the wave energy resource that can be harvested annually from the world's oceans is about 2000 TWh and can theoretically satisfy the current total amount of global demand for electricity [Agarwal, Venugopal, and Harrison, 2013]. Clearly, the highest energy waves are concentrated off the western coasts in the 30° - 60° latitude range north and south, i.e., the areas with the greatest winds, near the equator with persistent trade winds, and in high altitudes because of polar storms. Typical values of annual average wave energy flux for good offshore locations range between 20 and 70 kW/m.

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The power in the wave fronts varies in these areas between 30 kW/m and 70 kW/m with peaks to 100 kW/m. Thus, locations with the most potential for wave power include the western seaboard of Europe, the northern coast of the UK, and the Pacific coastlines of North and South America, Southern Africa, Australia, and New Zealand [Poullikkas, 2009]. The north and south temperate zones have the best sites for capturing wave power. However, seasonal variations are in general considerable larger in the northern than in the southern hemisphere, which makes the southern coasts of South America, Africa and Australia particularly attractive for wave power exploitation. The power in the wave fronts varies in these areas between 30 kW/m and 70 kW/m with peaks in the Atlantic Southwest of Ireland, the Southern Ocean and off Cape Horn.

Wave energy basic formulation

Waves are generated by wind blowing over the surface of the sea. As long as the waves propagate slower than the wind speed just above the waves, there is an energy transfer from the wind to the waves. Both air pressure differences between the upwind and the lee side of a wave crest, as well as friction on the water surface by the wind, making the water to go into the shear stress, causes the growth of the waves [Nihoul, 1981]. Wave height is determined by wind speed, the duration of time the wind has been blowing, fetch i.e., the distance over which the wind excites the waves and by the depth and topography of the seafloor which can focus or disperse the energy of the waves. In general, larger waves are more powerful but wave power is also determined by wave speed, wavelength, and water density.

Generally, wave power is considered to be the mean transport rate of the wave energy through a vertical plane of unit width, parallel to a wave crest, and is known as the wave energy flux provided by the equation:

$$P = \frac{\rho g^2 TH^2}{32\pi} \quad (1)$$

where P is the wave power in kW/m of crest length, i.e., per meter along the length of an individual wave crest, ρ is the seawater density in kg/m^3, g is the acceleration due to gravity in m/s^2, T is the period of the wave in s, and H is the wave height from crest, which is the highest point in a waveform, to trough, which is the lowest point in a waveform, in m.

However in deep water, where ocean waves exist, where the water depth is larger than half the wave wavelength, the wave energy flux is provided by a slightly different equation:

$$P = \frac{\rho g^2 TH_{mo}^2}{64\pi} \quad (2)$$

where H_{mo} is the significant wave height, defined as the average wave height, trough to crest, of the one third largest ocean waves. This means that a moderate ocean wave, a few kilometers offshore with a wave height of 3m and a wave period of 8s can provide 36 kW/m of power potential. In large storms, where typically waves offshore are about 15m high and have a wave period of about 15 s, waves can carry about 1.7 MW/m of power. However in practice, only a fraction of the wave power estimated in these cases can be effectively harnessed from a wave energy device [Korde and Ertekin, 2014].

A wave is travelling along the water surface with phase speed, which is well approximated by the equation:

$$c = \sqrt{\frac{g\lambda}{2\pi}\tanh\left(\frac{2\pi d}{\lambda}\right)} \quad (3)$$

where c is the wave phase speed in m/s, λ is the wavelength in m, measured from crest to crest, and d is the water depth in m.

In deep water where the depth is larger than half the wave wavelength and the hyperbolic tangent approaches 1, the wave speed approximates 1.25 $\sqrt{\lambda}$. This means that in deep water, the wave speed is hardly influenced by water depth, but is mostly dependent on the actual wave wavelength. Since the average wavelength of deep ocean waters is about 120 m, the average travelling speeds of these waves can reach 14 m/s. Essentially, waves of different wavelengths travel at different speeds and the fastest waves are the ones with the longest wavelength [Agarwal et al., 2013]. These waves are also typically the ones with the longest period T, which is the time interval between the arrival of consecutive crests at a stationary poinat. The fastest waves not only propagate faster, but can also transport their energy faster. In shallow water, where typically the wavelengths are larger than twenty times the water depth, the wave speed can be approximated by $\sqrt{gd}$ meaning that wave speed is only dependent on water depth and is no longer a function of wave period or wavelength.

Apart from the actual wave phase speed, in the cases where several waves are travelling together in groups, as is always the case in nature, the waves are also characterized by group speeds. The group speed of a wave is the speed with which the overall shape of the wave's amplitudes, known as the modulation or envelope of the wave, propagates through space. The group speed c_g is considered to be the speed at which wave energy is conveyed and transported horizontally along a wave. In deep water, the group speed is approximated as being half of the actual wave phase speed, while in shallow water, the group and the phase speed are considered to be equal. The wave group speed behaves differently for waves in deep or shallow water, therefore the wave energy transport speed will be different accordingly [Dean and Dalrymple, 1991]. The average energy density is provided by the following equation:

$$E = \frac{\rho g H_{mo}^2}{8} \quad (4)$$

where E is the mean wave energy density per unit horizontal area in J/m^2 and equals the sum of the kinetic and potential energy density per unit horizontal area. As can be expected from the equipartition theorem, the potential energy density is in fact equal to the kinetic energy density, thus both contribute equally to the wave energy density E. In deep water, such as ocean waves, the average energy density per unit area of ocean waves on the water surface is given by the following equation:

$$E = \frac{\rho g H_{mo}^2}{16} \quad (5)$$

As the ocean waves propagate, their energy is transported [Jeans, Fagley, Siegel, and Seidel, 2013]. The energy transport speed is the group speed as has been described above. As a result, and by using the wave power and energy density equations (2) and (5) for deep water and the fact that in deep water the group speed is half of phase speed, the ocean deep water wave power P in W/m, through a vertical plane of unit width perpendicular to the ocean wave propagation direction, is equal to:

$$P = Ec_g \quad (6)$$

with c_g being the deep water group speed in m/s [Nihoul, 1981; Goda, 2000].

Wave power generation technologies

The most important wave energy technologies that have been the target of recent research and development efforts are appropriate for onshore, near-shore or offshore applications. Onshore and near-shore systems are fixed or embedded near or on the shoreline. This has the advantage of easier installation and maintenance and would not require deep-water moorings or long lengths of underwater electrical cable [Fadaeenejad et al., 2014]. However, shoreline systems operate in a much less powerful wave energy regime compared to offshore systems. For example, offshore power densities could be 70 kW/m, while the same waves onshore can produce just 20 kW/m. In addition, as has been already discussed, shallow water wave behavior is largely unstable and potentially dangerous, since the potential wave breaking force could cause damages to wave energy devices infrastructure and equipment. Offshore wave energy devices, which are sometimes classified as third generation devices, are basically oscillating bodies, either floating or, more rarely, fully submerged. They exploit the more powerful wave regimes available in deep water, with typically more than 40 m water depth. Offshore wave energy converters are in general more complex compared with first generation systems. This, together with additional problems associated with mooring access for maintenance and the need of long underwater electrical cables, has hindered their development and only recently some systems have reached, or come close to, the full scale demonstration stage [Falcão, 2010]. However, as onshore devices are being perfected, the transfer to the more capital-intensive offshore projects may become more feasible and as experience is gained, less expensive. While all wave energy technologies are intended to be installed at or near the water's surface, they differ in their orientation to the waves with which they are interacting and in the manner in which they convert the energy of the waves into other energy forms, usually electricity. The most important technologies developed for wave energy devices are terminators, attenuators, point absorbers and overtopping devices [He et al., 2013].

However, each technology is still at an early stage of development to predict which technology or mix of technologies would be most prevalent in future commercialization. It is important to note that almost all of the currently installed wave energy devices are still at a prototype demonstration stage and have not yet provided electricity production at a commercial level (www.altprofits.com, 2013). Currently, only three wave energy projects can be classified as having achieved commercial status. These are the Pelamis (www.pelamiswave.com, 2013), the Limpet (www.bwea.com, 2013), (www.fujitaresearch.com, 2013) and the blueWAVE Oceanlinx (www.fujitaresearch.com, 2013) projects.

Terminators

Terminator devices extend perpendicular to the direction of wave travel and capture or reflect the power of the wave. These devices are typically installed onshore or near-shore and the device structure is typically fixed on the seabed or on the shore. However, floating versions have been designed for offshore applications. An indicative list of available terminator wave energy devices are tabulated in Table 1.

Table 1 Indicative list of installed terminator type wave energy devices (mid 2013)

Device	Company	Type	Status	Unit power (kW)	Country installed
blueWAVE	Oceanlinx	Offshore, floating OWC	Commercial	2500	Australia
Osprey	Wavegen	Fixed OWC	Prototype/ Abandoned	2000	UK
Limpet	Wavegen	Fixed OWC	Commercial	500	UK
European Power	European consortium	Fixed OWC	Prototype/ Demonstration	400	Portugal
Mighty Whale	JAMSTC	Ofshore, floating OWC	Prototype/ Demonstration	110	Japan

The oscillating water column (OWC) is a form of terminator device consisting of a partially submerged, hollow structure, which is open to the seabed below the waterline. As shown in Figure 2, water enters through a subsurface opening into a chamber with air trapped above it.

The heaving motion of the wave causes the captured water column to move up and down like a piston thus pressurizing and depressurizing the air though an opening connected to a turbine. The turbine is thus driven by the air flow to generate electricity. In OWC systems, typically a Wells turbine is employed which is a symmetrical bi-directional turbine, able to maintain constant direction of revolution despite the direction of the air flow passing through it. Therefore, a Wells turbine can effectively convert wave energy to electric energy irrespective of the heaving motion of a wave [Clément et al., 2002; Falcão, 2010].

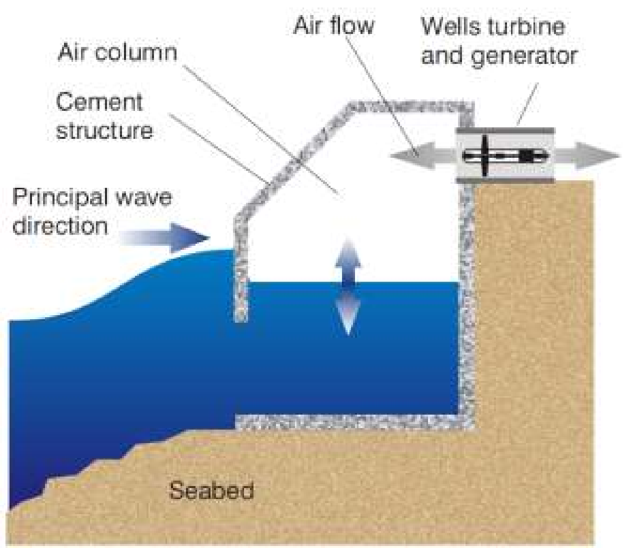

Figure 2 Principle of operation of a fixed structure OWC wave technology

A full-scale, floating offshore, 500 kW prototype OWC designed and built by Oceanlinx, previously Energetech, in 2006 has successfully undergone testing offshore at Port Kembla in Australia, providing both electric power and, via a desalination plant, fresh water at the test site facilities. A further Oceanlinx project is under development for Rhode Island. Finally, a 2.5 MWe final demonstration-scale, grid-connected unit near Port Kembla named blueWAVE, has successfully begun operations in early 2010, with electric power interconnected to the Australian grid [Babarit, 2013]. Oceanlinx is currently at the design stage for ten units to be located on the Oregon coast with a peak capacity of 15 MW. This has the potential to supply the power needs of about 15000 homes in the local area and will be one of the largest firm contract for a wave energy power company. These units will employ a Deniss-Auld bi-directional turbine, which is similar to a Wells turbine. Another floating offshore OWC is the Mighty Whale floating prototype, which has been under development at the Japan Marine Science and Technology Center since 1987. It consists of three air turbine generator units, one with a rated output of 50 kW and two of 30 kW.

Regarding onshore fixed structure OWC systems, typical examples include the Limpet and the European Power plant units. The Limpet system shown in Fig. 3, is a 500 kW OWC developed by the University of Belfast and the Scottish company Wavegen Ltd in the UK, on the Isle of Islay in Scotland. Although most previous OWC systems have had vertical water columns, the Limpet system is angled at 45° which wave tank tests show to be more efficient. The Limpet is the direct successor of an experimental 75 kW turbine, built by researchers from the Queen's University of Belfast, which operated on the island of Islay between 1991 and 1999. The Limpet system has been successfully connected to the Scottish electricity grid since September 2000. The system is under constant monitoring in order to address many of the issues currently hindering the full-scale deployment of OWC devices. Another Limpet unit, at pilot plant scale, is currently being developed in the Azores [www.bwea.com, 2013], [www.fujitaresearch.com, 2013].

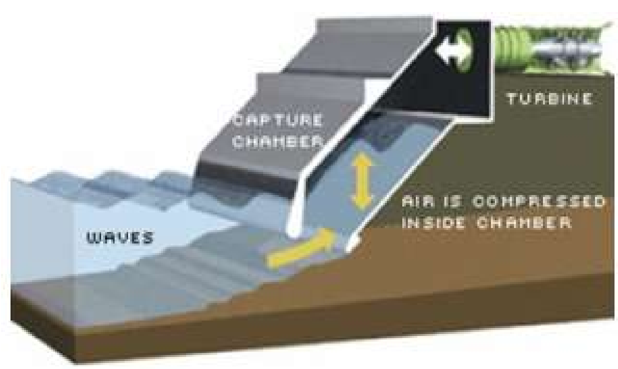

Figure 3 Principle of operation of Limpet OWC wave technology

The European Power plant, shown in Fig. 4, is a 400kW OWC developed by a European consortium of 8 partners, 2 from the UK and 6 from Portugal, on the Pico island in the Azores in 1999. The plant was originally designed as a full-scale testing facility, with the ambition of being able to supply a sizable part of the island's energy demand. However, the plant has so far been operational for only a limited amount of time of a total of 265 hours in 2009.

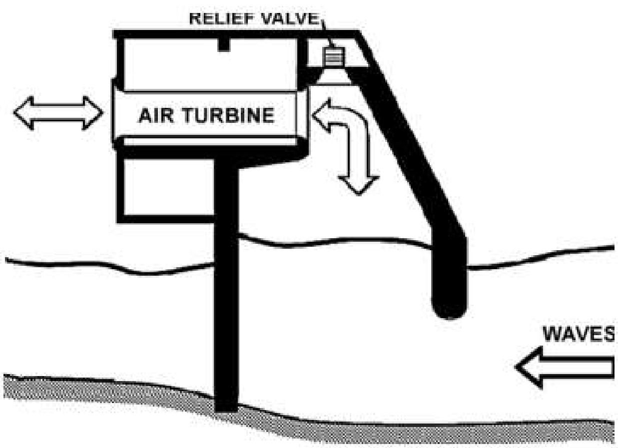

Figure 4 Principle of operation of European Power OWC wave technology

Attenuators

Attenuators are long multi-segment floating structures oriented parallel to the direction of the wave travel. The differing heights of waves along the length of the device causes flexing where the segments connect, and this flexing is connected to hydraulic pumps or other converters. The attenuators with the most advanced development are the floating attenuators such as the McCabe wave pump and the Pelamis machines developed by Pelamis Wave Power Ltd. However, the first known attenuator prototype was the Duck device, introduced in 1974. An important feature of this device was its ability to convert both the kinetic and potential energies of the wave, achieving thus very high absorption efficiencies which could theoretically reach over 90%. Despite the promise of low electricity production costs, and although the Duck concept was the object of extensive R&D efforts for many years, including model testing at several scales, it never reached the stage of full-scale prototype deployment in real seas (Barbariol et al., 2013). A summary of available attenuator wave energy devices are shown in Table 2.

Table 2 Indicative list of installed attenuator type wave energy devices (mid 2013)

Device	Company	Type	Status	Unit power (kW)	Country installed
Pelamis	Wavegen	Offshore, floating	Commercial	750	Portugal
McCabe wave pump	Hydam Technology	Offshore, floating	Prototype/ Demonstration	400	Ireland
Oyster	Aquamarine Power	Fixed on seabed near-shore/partly submerged	Prototype/ Demonstration	350	UK
WaveRoller	AW- Energy Oy	Fixed on seabed near-shore/fully submerged	Prototype/ Demonstration	300	Portugal

The McCabe wave pump, shown in Fig. 5, has three pontoons linearly hinged together and pointed parallel to the wave direction. The center pontoon is attached to a submerged damper plate, which causes it to remain still relative to the forward and aft pontoons (López and Iglesias, 2014). Hydraulic pumps attached between the center and the two end pontoons are activated as the waves force the end pontoons up and down. The pressurized hydraulic fluid can be used to drive a motor generator or to pressurize water for desalination. A full-size 40-m prototype was tested off the coast of Ireland in 1996, with a 40 kW power rating.

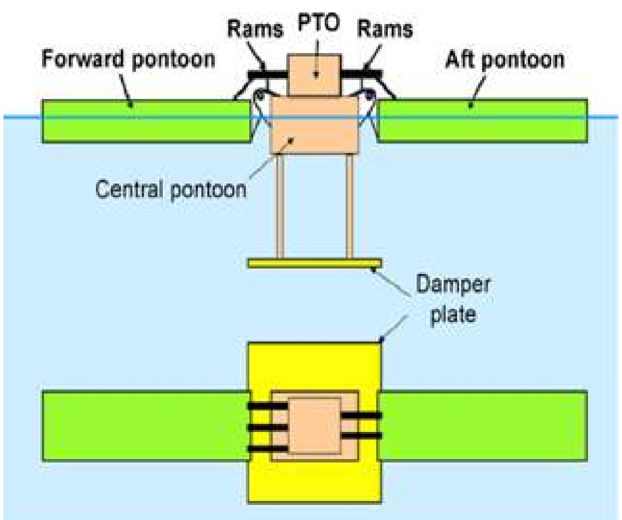

Figure 5 Principle of operation of McCabe wave pump

A similar concept is used by the Pelamis machine which has four 35 m long by 3.5 m diameter floating cylindrical sections connected by three hinged joints as shown in Fig. 6. The Pelamis technology is intended for general deployment and operation offshore with water depths of 50 m – 70 m and with nominal wave power of 55 kW/m. The four sections of the device articulate with the movement of the waves, each resisting motion between it and the next section [Bouali and Larbi, 2013]. In this way, as waves run down the length of the device, since it is positioned parallel to the direction of wave travel, flexing at the hinged joints due to wave action pumps pressurized oil to drive hydraulic pumps and motors built into the joints. Electricity generated in each joint is transmitted to shore by a sub-sea cable.

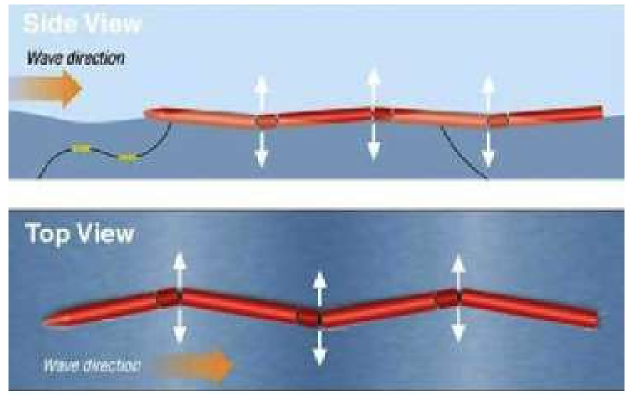

Figure 6 Principle of operation of Pelamis wave technology

A full-scale, four-section production prototype rated at 750 kW was sea tested for 1000 hours in 2004. This successful demonstration was followed by the first order in 2005 of a commercial system from a consortium led by the Portuguese power company Enersis SA. The first stage was completed in 2006 and consists of three Pelamis machines of type P1, which is made up of three power conversion sections per machine, each rated at 250 kW with a combined rating of 2.25 MW sited about 5 km off the coast of northern Portugal near Povoa de Varzim. This wavefarm, called the Agucadoura wave farm, was the world's first commercial wave farm and it first generated electricity in July 2008. However, the wave farm was shut down in November 2008, as a result of financial issues. A Pelamis-powered 20MW wave energy facility, is currently under development in Scotland and will be using the second generation P2 Pelamis machines which contain four conversion sections per machine, with a nominal power rating of 750 kW per machine and expected capacity factor to range between 25% - 40% and peak annual generation 2.7 GWh per machine [www.pelamiswave.com, 2013].

Apart from the Agucadoura wave farm, described previously relating to the Pelamis machines, funding for a 3 MW wave farm in Scotland was announced in 2007. The first of 66 Pelamis machines was launched in May 2010. Funding has also been announced for the development of a Wave hub off the north coast of Cornwall, England. The Wave hub will act as giant extension cable, allowing arrays of 40 wave energy generating devices to be connected to the electricity grid. The Wave hub will initially allow

20 MW of capacity to be connected, with potential expansion to 40 MW.

Four device manufacturers have so far expressed interest in connecting to the Wave hub. It is estimated that wave energy gathered at Wave Hub will be enough to power up to 7500 households [López and Iglesias, 2014]. Savings that the Cornwall wave farm will bring are significant, reaching about 300,000 tons of carbon dioxide to be avoided in the next 25 years.

Finally, the 350 kW Oyster wave energy converter, shown in Fig. 7, is a hydro-electric wave energy device developed by Aquamarine Power. The wave energy device captures the energy found in near shore waves and converts it into electricity. The system consists of a hinged mechanical flap connected to the seabed at around 10m depth. Each passing wave moves the flap which drives hydraulic pistons to deliver high pressure sea-water via a pipeline to an onshore Pelton type turbine which generates electricity. In November 2009, the first full-scale demonstrator Oyster began producing power when it was launched at the European Marine Energy Centre on Orkney region in Scotland. Similar to the Oyster device is the WaveRoller, a Finish fully submerged device, which is another seabed-hinged device. However, the WaveRoller system topology is totally submerged and uses oil as a working fluid. A 3.5 m high, 4.5 m wide prototype of the WaveRoller was deployed and tested in 2008 close to the Portuguese coast at Peniche [Falcão, 2010][www.bwea.com, 2013][www.aw-energy.com, 2013].

Figure 7 The Oyster prototype manufactured by Aquamarine Power

Point absorbers

Point absorbers have a small horizontal dimension compared with the vertical dimension and utilize the rise and fall of the wave height at a single point for wave energy conversion. These devices are basically offshore oscillating bodies, either floating or fully submerged. They exploit the more powerful wave regimes available in deep water. The available point absorber wave energy devices are tabulated in Table 3.

Table 3 Indicative list of installed point absorber type wave energy devices (mid 2013)

Device	Company	Type	Status	Unit power (kW)	Country installed
Archimedes Wave Swing	Teamwork Technology BV	Fixed near shore, fully submerged	Prototype/ Demonstration	2000	Portugal
CETO	Carnegie Wave Energy	Fixed near shore, fully submerged	Prototype/ Demonstration	400	Australia
AquaBuOY	Finavera Renewables	Offshore, floating non-fixed	Prototype/ Demonstration	250	USA
Swedish buoy (Lysekil)	Uppsala University	Fixed offshore	Prototype/ Demonstration	To reach 100	Sweden
PowerBuoy	Ocean Power Technologies	Ofshore, floating non-fixed	Prototype/ Demonstration	50	USA
SDE	SDE Energy	Fixed near shore	Prototype/ Demonstration	40	Israel

Floating point absorbers are divided into two categories, depending on whether the bottom end of the structure is fixed to the sea-bed or to a bottom-fixed structure, or if it is allowed to be in motion. Currently, the major point absorbers with a non-fixed bottom end include the PowerBuoy and the AquaBuOY. The PowerBuoy was developed by Ocean Power Technologies and is shown in Fig. 8. The construction involves a cylindrical structure with one component relatively immobile as the bottom end, and a second component with movement driven by wave motion as the top end floating buoy inside a fixed cylinder [Korde and Ertekin, 2014].

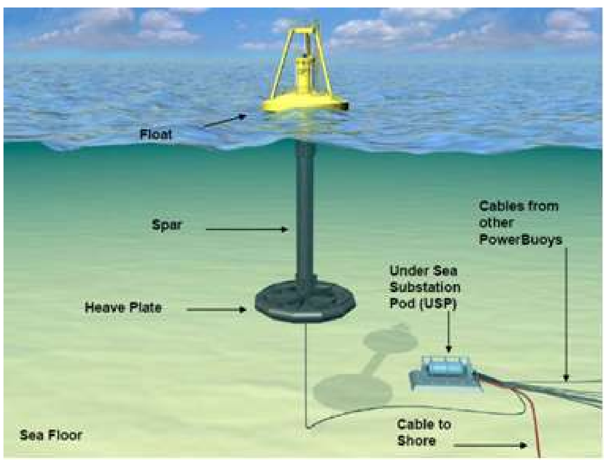

Figure 8 Principle of operation of PowerBuoy wave technology

The relative motion of the two components which is caused by the rising and falling of the waves is used to drive electromechanical generators or hydraulic energy converters. The electric power generated is transmitted to shore over a submerged transmission line. A 150 kW buoy has a diameter of 11 m and is 44 m tall, with approximately 10m of the unit rising above the ocean surface. Using a three-point mooring system, these devices are designed to be installed 2 to 8 km offshore in water up to 60 m deep. A PowerBuoy demonstration unit rated at 40 kW was installed in 2005 for testing offshore from Atlantic City, New Jersey. In addition, recently, the Pacific Northwest Generating Cooperative is funding the building of a commercial wave-power park in Oregon utilizing this technology. Testing in the Pacific Ocean is also being conducted, with a 50 kW unit installed in 2004 and 2005 off the coast of the Marine Corps Base in Oahu, Hawaii. A commercial-scale PowerBuoy system is planned for the northern coast of Spain, with an initial wave park consisting of multiple units of 1.25 MW rating [Falcão, 2010] [www.bwea.com, 2013].

The AquaBuOY unit shown in Figure 9 being developed by the Finavera Renewables, is a point absorber that is the third generation of two Swedish designs [Anbarsooz et al., 2014]. These designs are the original and the sloped IPS buoys, which utilize the wave energy to pressurize a fluid that is then used to drive a turbine generator. The vertical movement of the top floating buoy drives a broad, neutrally buoyant disk acting as a water piston contained in a long tube beneath the buoy. The water piston motion in turn elongates and relaxes a hose containing seawater, and the change in hose volume acts as a pump to pressurize the seawater. The AquaBuOY design has been tested using a full-scale prototype, and a 1 MW pilot offshore demonstration power plant is being developed offshore at Makah Bay, Washington. The Makah Bay demonstration will include four units rated at 250 kW placed 5.9km offshore in water approximately 46m deep.

Figure 9 Principle of operation of AquaBuOY wave energy technology

Point absorbers with a fixed bottom end that have been tested at prototype scale include the Archimedes Wave Swing, as illustrated in Fig. 10, developed by Teamwork technology BV of Netherlands, which consists of an oscillating upper part, called the floater and a bottom-fixed lower part called the basement. The floater is pushed down under a wave crest and moves up under a wave trough. This motion is resisted by a linear electrical generator, with the interior air pressure acting as a spring. The AWS device went for several years through a programme of theoretical and physical modeling. A prototype was built, rated at 2 MW of maximum instantaneous power [Montoya et al., 2014]. The AWS was the first converter using a linear electrical generator.

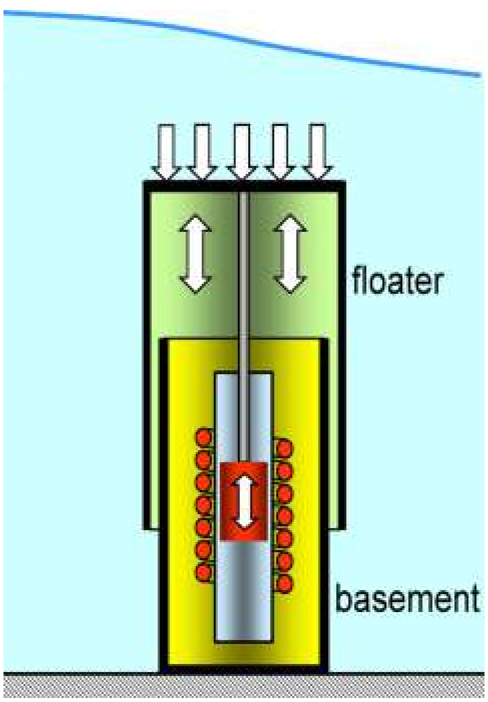

Figure 10 Principle of operation of the Archimedes wave swing

A wave energy device called CETO is also currently being tested off Fremantle in Western Australia. The device consists of piston pumps attached to the sea floor, at a 20 m -50 m water depth, with a fully submerged float tethered to the piston. The oscillatory motion of the float due to water motion generates pressurized water from the pistons, which is piped to an onshore facility to drive hydraulic generators or run a reverse osmosis water desalination plant. The Lysekil Project wave energy device shown in Fig. 11, is located on the Swedish west coast about 100 km north of Gothenburg, close to Lysekil.

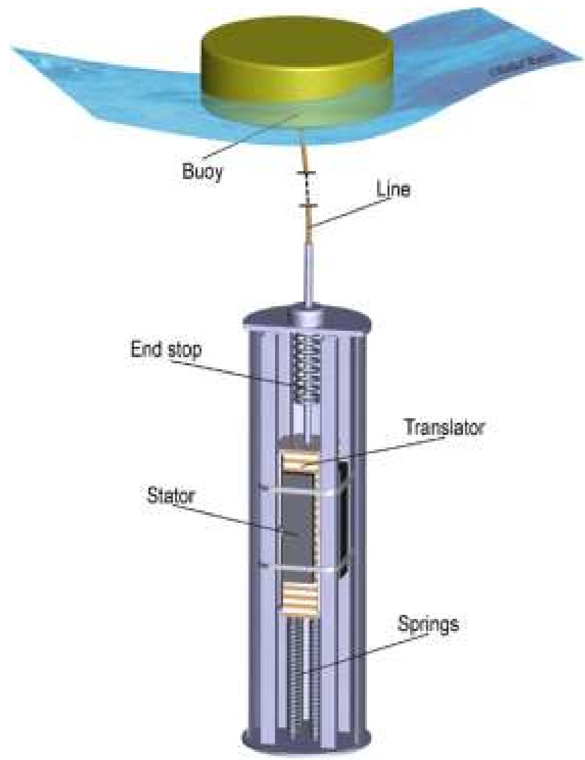

Figure 11 Principle of operation of Lysekil wave energy device employing a linear generator

The site is located 2 km offshore and covers an area of 40000 m^2. The wave power concept in the Lysekil project is based on a three phase permanent magnetized linear generator placed on the seabed. The linear generator is connected to a point absorbing buoy at the surface via a line. When the waves move, the hydrodynamic action forces the buoy to move in a heaving motion. The movements of the buoy will then drive the translator in the generator, consequently inducing current in the stator windings. The translator is connected to the generator foundation with springs that retract the translator in the wave troughs [Leijon et al., 2008]. Finally, the Israeli firm SDE ENERGY LTD has developed a 40 kW near-shore wave energy converter. This device utilizes the vertical motion of buoys for creating a hydraulic pressure, which in turn operates the system's generators. SDE is currently preparing to construct its standing order for two 100 MW wave energy power plants, one in each of the islands of Zanzibar and Kosrae in Micronesia.

Overtopping devices

Overtopping devices have reservoirs that are filled by impinging waves to levels above the average surrounding ocean. The released reservoir water is used to drive hydro turbines or other conversion devices. Overtopping devices have been designed and tested for both onshore and floating offshore applications. A summary of available overtopping wave energy devices are tabulated in Table 4.

Table 4 Indica Overtopping type wave energy devices installed

Device	Company	Type	Status	Unit power (kW)	Country installed
Wave Dragon	Wave Dragon	Offshore, floating	Prototype/ Demonstration	4000 - 7000	Denmark
Tapchan	Norware	Fixed, onshore	Prototype/ Demonstration	350	Norway
Floating Wave Power Vessel	Sea Power International	Ofshore, floating	Prototype/ Demonstration	N/A	Sweden

The offshore devices include the Wave Dragon, as illustrated in Fig. 12, whose design includes wave reflectors that concentrate the waves toward it and thus raises the effective wave height. Electricity is produced by a set of low-head Kaplan turbines. Wave Dragon development includes a 7 MW demonstration project off the coast of Wales and a pre-commercial prototype project performing long-term and real sea tests on hydraulic behavior, turbine strategy, and power production to the grid in Denmark. The Wave Dragon design has been scaled to 11 MW, but larger systems are feasible since the overtopping devices do not need to be in resonance with the waves as is the case for point absorbing devices.

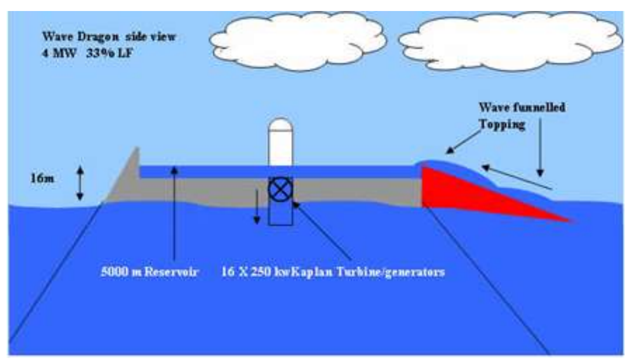

Figure 12 Principle of operation of Wave Dragon overtopping device

Also, the Floating Wave Power Vessel is an offshore overtopping design developed by Sea Power International, Sweden, consisting of a floating basin supported by ballast tanks in four sections and an anchor system that allows the direction of the vessel to the highest energy potential wave. A pilot plant has been deployed in the 1980's near Stockholm, Sweden, and a 1.5 MW vessel is planned to be deployed at 50 to 80 m depth at a distance of 500 m offshore the Mu Mess area in Scotland [Anbarsooz et al., 2014]. Finally, the WavePlane overtopping device has a smaller reservoir. The waves are fed directly into a chamber that funnels the water to a turbine or other conversion device.

An example of an onshore overtopping system is the Tapchan (Tapered Channel Wave Power Device) system, shown in Fig. 13, developed in Norway by Norwave. The prototype has a rated power of 350 kW and was built in 1985 at Toftestallen, Norway, and operated for several years. The Tapchan comprises a collector, a converter, a water reservoir and a low-head water-turbine. The horn-shaped collector serves the purpose of concentrating the incoming waves before they enter the converter. In the prototype, the collector was carved into a rocky cliff and was about 60 m wide at its entrance.

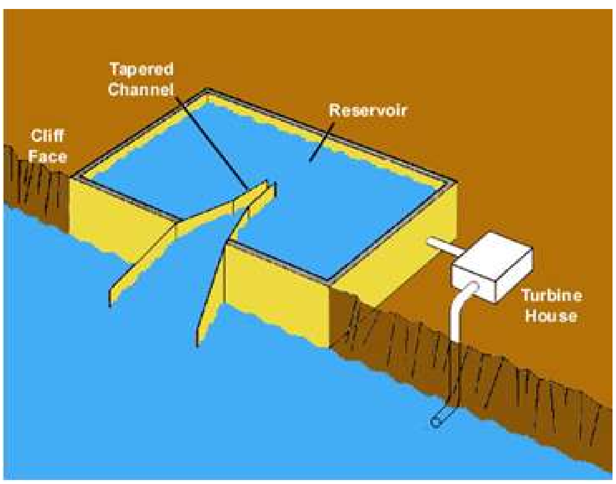

Figure 13 Principle of operation of Tapchan overtopping device

The converter is a gradually narrowing channel with wall heights equal to the filling level of the reservoir, which is about 3 m in the Norwegian prototype. The waves enter the wide end of the channel, and, as they propagate down the narrowing channel, the wave height is amplified until the wave crests spill over the walls and fill the water reservoir. As a result, the wave energy is gradually transformed into potential energy in the reservoir. The main function of the reservoir is to provide a stable water supply to the turbine. It must be large enough to smooth out the fluctuations in the flow of water overtopping from the converter, about 8500 m^2 surface area in the Norwegian prototype. A conventional low-head Kaplan-type axial flow turbine is fed in this way, its main specificity being the use of corrosion-resistant material [Falcão, 2010].

Wave to electricity conversion technologies

Wave power generation technologies essentially capture wave energy and convert it into electrical energy to be supplied to the electrical grid. Essentially, the electrical energy has to be generated in some kind of electrical machine which can be either a conventional rotating generator as in small hydro or wind applications or a direct drive linear generator.

Conversion using conventional generators

In order to adequately drive a conventional generator, there has to be a mechanical interface between the wave energy device and the electricity generator to convert the alternative and irregular motion of the device, which moves with the irregular bi-directional motion of the waves, into a continuous one-directional motion to drive the generator [Ahmed et al., 2013]. The situation is more demanding in terminator or OWC devices, since the motion of the wave is not only irregular but also bi-directional and, as such, cannot be tolerated by a conventional generator. In addition, wave energy is characterized by large forces and low velocities due to the characteristic of ocean waves. As conventional generators are designed for high speed rotational motion, wave energy devices using conventional generators need to integrate a number of intermediate steps, for example hydraulics or turbines, to convert this slow-moving wave motion making it suitable for these generators [Montoya et al., 2014].

There are currently three major mechanical interfaces used today for converting wave into electrical energy via use of a conventional generator. These are the self-rectifying air turbine, the high or low-head hydraulic turbine and the high-pressure oil-driven hydraulic motor. Typically, air turbines are used with terminator or OWC devices, high-head hydraulic turbines are used with attenuator and point absorber technologies, as alternative to hydraulic motors, while low-head hydraulic turbines are typically used with overtopping technology devices [Falcão, 2010].

Air turbines

The self-rectifying air turbines are typically used in all terminator or OWC devices. The reason is that these turbines allow a single directional flow of air through to the conventional generator [Anbarsooz et al., 2014]. These self-rectifying air turbines, especially the fixed-geometry ones, are mechanically simple and reliable machines. Based on available information, their time-averaged efficiency is relatively modest, compared with more conventional turbines operating in near steady state conditions, hardly exceeding 50% - 60%, even if their rotational speed is controlled to match the current sea state, especially the significant wave height.

The Wells turbine is the most frequently used air turbine today. The most favourable features of the Wells turbine are: (a) high blade to air-flow velocity ratio, which means that a relatively high rotational speed may be attained for a low velocity of air flowing through the turbine thus allowing a cheaper generator to be used and also enhancing the possibility of storing energy by flywheel effect, (b) a fairly good peak efficiency of 70% - 80% for a full-sized turbine and (c) is relatively cheap to construct. The weak points of the Wells turbine are: (a) low or even negative torque at relatively small flow rates, (b) drop in power output due to aerodynamic losses at flow rates exceeding the stall-free critical value, (c) aerodynamic noise and (d) a relatively large diameter for its power such as 2.3 m for the single-rotor 400 kW turbine of the Pico OWC plant, 2.6 m for the counter-rotating 500 kW turbine of the Limpet plant and 3.5 m for the OSPREY plant [Borg et al., 2013].

The most important variation of the Wells turbine is the Kaplan turbines which uses variable pitch rotor blades. The general concept is that if the rotor blade pitch angle is adequately controlled, a substantial improvement in time-averaged turbine efficiency can be achieved. The negative side is that the resulting turbine is a more complex and more expensive machine compared to the conventional Wells turbine. A full sized prototype of a Kaplan turbine has been designed and constructed to be installed in the Limpet Azores OWC. Other alternative variations to the Wells turbine include the self-rectifying impulse turbine and the Deniss-Auld turbine, developed in Australia to equip the blueWAVE Oceanlinx OWC plant. The Deniss-Auld turbine is also a self-rectifying turbine that shares some characteristics with the variable pitch turbine, the main difference being the range of variation of the angle of stagger.

Hydraulic turbines

As in conventional mini-hydroelectric low-head plants, low-head axial-flow reaction turbines are used to convert the head, typically 3 m – 4 m at full size, created between the reservoir of an overtopping device and the mean sea level. The flow may be controlled by adjustable inlet guide vanes. In some cases the blades of the runner can also be adjusted which greatly improves efficiency over a wide range of flows. However this can be costly and is not normally employed in the small turbines typical of wave energy applications.

High-head, typically tens to hundreds of meters, impulse turbines mostly of Pelton type are adopted in some attenuator or point absorber devices, as alternatives to hydraulic motors, with the advantage of using non-pollutant water rather than oil. The flow may be controlled by a needle whose axial position within the nozzle is controlled by a servomechanism. The hydraulic circuit includes a ram and may include also a gas accumulator system [Guanche et al., 2013]. These low and high head hydraulic turbines may reach peak efficiencies of about 90%. Their efficiency is in general quite sensitive to the head-to-rotational-speed ratio, which makes the use of variable speed electrical generators highly advantageous, especially in the case of Pelton turbines equipping point absorber devices.

High pressure oil hydraulic motors

High-pressure oil systems as shown in Fig. 14 are particularly suitable to convert energy from the very large forces or moments applied by the waves on slowly oscillating bodies either in translation or in rotation. The hydraulic circuit usually includes a gas accumulator system capable of storing energy over a few wave periods, which can smooth out the very irregular power absorbed from the waves. The body motion is converted into hydraulic energy by a hydraulic cylinder or ram. A fast hydraulic motor drives a conventional electrical generator [Malara and Arena, 2013].

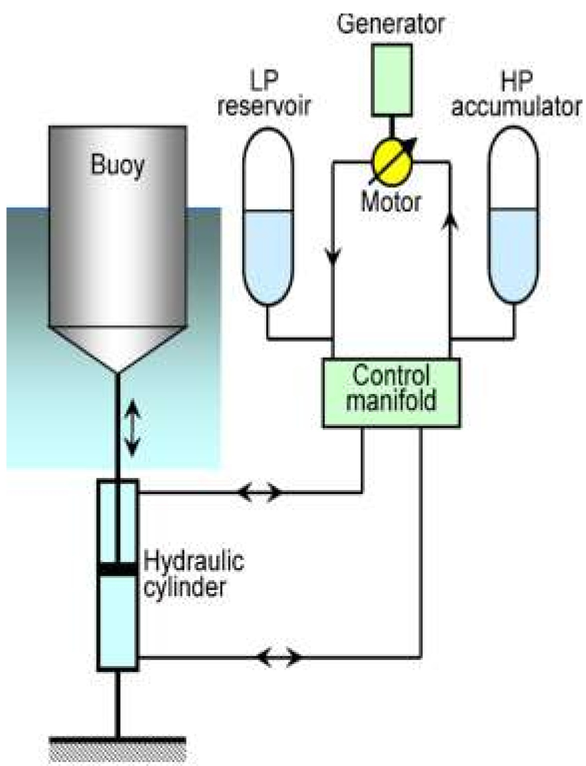

Figure 14 Principle of operation of the hydraulic mechanism employed in point absorbing or attenuator wave energy devices

The oil-hydraulic mechanical interface was recently used to equip the PowerBuoy point absorbing device and attenuator devices such as the Pelamis and the WaveRoller wave energy device. Although little has been disclosed on the performance of recent sea-tested prototypes equipped with hydraulic mechanical interfaces, it appears that some concerns are related to lower than expected energy conversion efficiency and the limited estimated lifespan of hydraulic ram seals. New designs of hydraulic equipment, specifically for wave energy applications, may be the way to solving these problems.

Electrical equipment

In the wave energy converters discussed above, a rotating electrical generator is driven by a mechanical machine interface, which can be air or hydraulic turbine, or a hydraulic motor. In such cases the regulating electrical equipment, including variable rotational speed and power electronics, required at the connection point to the grid, is mostly simple and conventional and largely similar to wind energy conversion systems. In the case that the driving machine is a variable displacement hydraulic motor, it is possible to keep the rotational speed fixed while controlling the flow rate and power by adjusting the motor geometry.

Conversion using direct drive linear generators

A different way to address the issue of converting the wave energy into grid-quality electrical energy is by adapting the electric generator system to the motion of the waves. This can be done by using a direct driven wave energy converter with a linear generator. Direct drive has the advantage of not requiring a mechanical interface and therefore avoiding the non-negligible losses that take place in the mechanical machines, such as the turbines and hydraulic motors, in more conventional wave energy systems. It also requires a less complex mechanical system with potentially a smaller need for maintenance.

On the other hand, linear electrical generators for wave energy applications are subject to much more demanding conditions than high-speed rotary ones because the generator reciprocating motion matches the motion of the actual device, at speeds two orders of magnitude lower than the velocities typical of high-speed rotary generators. At such low speeds, the forces are very large, which requires a physically large machine. Moreover, linear electric generators are to a large extent still at the development stage in several countries such as Holland, UK, Sweden and USA. In addition, this type of system requires a much more complicated power electronics block to enable the connection of the electrical power to the grid. This is due to the characteristics of the generated voltage which varies widely both in amplitude and frequency.

Linear generator

The moving part in a linear generator is called translator, rather than rotor, and when the buoy is lifted by the wave the buoy sets the translator in motion. It is the relative motion between the stator and the translator in the generator, which causes voltage to be induced in the stator windings [López et al., 2013]. The requirement on a linear generator for wave power applications is the ability to handle high peak forces, low speed and irregular motion at low costs. When a generator moves with varying speed and direction it results in an induced voltage with irregular amplitude and frequency. The output power's peak value will be several times higher than the average power production. The generator and the electrical system have to be dimensioned for these peaks in power.

There are different kinds of linear generators which could be used in wave power applications and it has been found that permanent magnetized synchronous linear generators seem to be the most suitable type. In the Lysekil project this type of generator has been chosen and the magnets are Nd/Fe/B permanent magnets mounted on the translator. Inside the generator powerful springs are fastened underneath the translator, and act as a reacting force in the wave troughs after the buoy and translator are lifted by the wave crests [Borg et al., 2013]. The springs also temporarily store energy which results in allowing the generator, optimally, to produce an equal amount of energy in both directions, evening out the produced power. In the top and bottom of the generator end stops with powerful springs are placed to limit the translator stroke length [Leijon et al., 2008].

Electrical equipment

The power produced cannot, as mentioned earlier, be directly delivered to the grid without conversion. This is done in several steps. Firstly, the voltage is rectified from each generator. Then the voltage outputs are interconnected in parallel and the resulting output DC voltage is filtered through capacitive filters [Heras-Saizarbitoria et al., 2013]. The filters smooth out the voltage from the generators and create a stable DC voltage. During short periods of time, the power after the filter will also be constant. If the system is studied during hour-scales, or more, there will be variations in the produced power and these variations are due to changes in the sea state.

This concept does not apply in the cases where a single wave energy device unit is to be operated. This is mainly due to the large short-term variations in produced power and the relatively small size of the unit and because the cost for the electrical conversion system would be too high. When several generators are connected in parallel, the demand on the ability of the capacitive filter to store energy will decrease and hence also the cost associated with it. To compensate for voltage variations on the output that occur due to sea state variations, a DC/DC converter or a tap-changed transformer can be used.

System aspects

A high level of damping, i.e., power extraction, results in bigger difference between the vertical motion of the wave and the speed of the translator. This will in turn result in a higher line force when the wave lifts the buoy and a lower force when the buoy moves downwards. The maximum power occurs during the maximum and minimum line forces assuming the translator is within generator stroke length. If the translator moves downwards with a lower speed than the buoy, the line will slacken and the resulting line force will become almost zero. The reverse relation occurs when the buoy moves upwards. In this case, the line force becomes larger the bigger difference there is between the motion of the buoy and the generator translator [Leijon et al., 2008].

If the wave height, i.e. the difference between wave crest and wave trough, is larger than the stroke length the translator will reach a standstill at the lower end stop. At the upper end stop the wave flushes over the buoy and at the lower the line slackens. In both of these cases no power is produced and no voltage is induced until the translator starts to move again [Leybourne et al., 2014]. This happens when the wave is lower than the buoy's top position in the upper state, and in the lower state when the wave has risen so much that the buoy once again starts to pull the translator upwards. It has been found that most of the energy is transmitted through wave heights of 1.2 m - 2.7 m.

If the generator is connected to a linear strictly resistive load, it will deliver power as soon as voltage is induced in the generator. With a non-linear load the relation is not so simple. The load is not linear due to the transmission system, whose diode rectifier results in power only being able to be extracted over certain voltage levels [López et al., 2013]. Consequently the DC voltage level limits the amplitude of the generator phase voltage. With a non-linear load the generator phase voltage will reach maximum amplitude which is approximately equal to the DC voltage. When the generator's phase voltage reaches the level of the DC voltage current starts to flow from the generator to the DC side of the rectifier. Power will be delivered as long as the waves can deliver mechanical power to the buoy and as long as the translator has not reached its upper or lower end stop. The current will increase when the speed of the translator increases. This non-linear power extraction results in different shapes of the voltages and the current pulses.

Economics of wave energy

Generally, the capital cost of wave energy devices is significantly higher than any operating and maintenance costs and therefore capital expenditure is essentially the main expenditure influencing the final cost of electricity generation from wave energy devices. The level of capital expenditure is dependent on the type of wave energy device and on the distance of its location from the shoreline. Also, the operation and maintenance costs are technology dependent as well as distance from the shore depended with high uncertainty.

Capital cost estimations

The main barrier to global widespread wave energy devices implementation is the high initial investment. Despite the fact that the overall maintenance cost of wave energy devices is low, the initial capital cost investment is significantly high to hinder investment and thus development of such technology. Apart from the high cost of materials, one reason for the high cost of the initial investment is the need to make the equipment impervious to storm damage and corrosion. In fact, most of the existing wave energy devices designs have been heavily over-engineered to reduce the chances of breakdown at sea. This also includes special mooring designs. Finally, due to the fact that development of such technology is still in its early stages and thus has not benefited from economies of scale or the efficiency that comes with experience, the costs remain very high and commercial prospects cannot be assessed with certainty [Fadaeenejad et al., 2014].

Generally, onshore or near shore wave energy devices offer more economical solutions in terms of capital cost compared to offshore devices. Onshore devices are more easily installed and maintained and do not require deep-water moorings or other specialized infrastructure. In addition, there is no need for long underwater electrical cables to carry the electrical energy onshore. Finally, funding for onshore wave energy devices may be justified by other funding needs of the local coastal communities such as shore erosion if wave energy devices can be integrated into breakwater or other structures built for wave protection and sheltering [Bouali and Larbi, 2013]. Because onshore wave energy devices are usually located close to other infrastructures, the costs of construction, installation, power transfer and maintenance can be reduced considerably compared to offshore wave power generators. However, as has already been mentioned, the onshore or near shore environment offers lower wave energy flux and potential due to lower wave energies compared to offshore ocean areas [Teillant et al., 2012].

The capital cost estimation of wave energy devices is a complex procedure since it depends on many physical factors such as system design, wave energy power, water depth, distance from the shore and ocean floor characteristics. In addition, cost estimates of existing wave energy projects is difficult since in most cases the estimates are based on continuously evolving designs of prototypes. An estimate of wave energy device capital cost could be provided for example by the first Pelamis wave farm built in Portugal. This project represented an 8 million euro investment with a total of three 750 kW devices, having therefore a capital cost of 3555 €/kW [Simmonds et al., 2010]. This is higher than the capital cost of photovoltaic systems and approximately four times higher than the capital cost of large-scale wind turbines. It has been reported that the capital costs of current wave energy devices range from 3000 €/kW up to more than 11000 €/kW suggesting that significant breakthroughs in capital cost would be necessary to make this technology cost competitive with other renewable energy technologies [US Department of the Interior, 2006].

Electricity generation costs

The high capital cost of wave energy devices is translated into high electricity generation costs compared to other renewable energy sources and, of course, compared to conventional and established electricity generation technologies [Smith et al., 2013]. For example, the Pelamis wave farm in Portugal would have an electricity unit cost of almost 0.30 €/kWh, using capital expenses of € 8million and assuming zero operation and maintenance costs and the highest capacity factor of 40% i.e., an annual electricity generation of 2.7 GWh. Clearly, the electricity generation cost would depend on the wave energy potential of the actual geographical position of the installation. Furthermore based on [Previsic et al., 2004] electrical energy from wave energy projects would cost between 0.133 €/kWh and 0.48 €/kWh. Also based on [Falcão, 2010] in 2020 the cost of energy from wave energy projects would range between 0.11 €/kWh to 0.25 €/kWh [Simmonds et al., 2010].

In Previsic et al. [2004] the projected electricity generation costs for wave energy projects for possible installation in USA coastal areas was calculated. A design, performance, and cost simulation assessment was conducted for an Ocenalinx commercial-scale OWC with a 1,000 kW rated capacity, sited 22 km from the California shore. With the wave conditions at this site which provide average annual wave energy of 20 kW/m, the estimated annual energy produced was 1973 MWh/yr. For a scaled-up commercial system with multiple units producing 300,000 MWh/yr, the estimated cost of electricity would be on the order of 0.075 €/kWh [US Department of the Interior, 2006]. The Pelamis technology also modelled for design, performance, cost, and economic assessment [Previsic et al., 2004]. Sites for evaluation were selected off the coasts of Hawaii, with an 15.2 kW/m average annual wave energy, Oregon at 21 kW/m, California at 11.2 kW/m, Massachusetts at 13.8 kW/m, and Maine at 4.9 kW/m. For systems at these sites scaled to a commercial level generating 300,000 MWh/yr, the cost of electricity ranged from about 0.075 €/kWh for the areas with high wave energy, to about 0.029 €/kWh for Maine, which has relatively lower levels of wave energy [López et al., 2013]. The same source cites that commercial wave energy projects in offshore regions of California, Hawaii, Oregon and Massachusetts could be in the range of 0.066 €/kWh to 0.081 €/kWh [Teillant et al., 2012]. The report estimates that improving technology and economies of scale will allow wave generators to produce electricity at a cost comparable to wind driven turbines, which currently produce energy at about 0.045 €/kWh [US Department of the Interior, 2006].

Conclusions

In this work, a comparative overview of wave power technologies was carried out. Although the wave energy resource is theoretically enormous, it is only located in certain areas of the globe where sufficiently high wave power potential exists. These areas are the western seaboard of Europe, the northern coast of the UK and the pacific coastlines of North and South America, Southern Africa, Australia and New Zealand. In addition, the highest potential exists in deep ocean waters, many kilometers offshore. Therefore, only a fraction of the wave energy resource can be harnessed by current wave energy technologies. Currently, wave power technologies are neither mature nor have become widely commercialized. Although these technologies can cover onshore, near-shore and offshore applications, the vast majority of wave energy devices developed today from these technologies is still in prototype demonstration stage. It is, therefore, too early to predict which of these technologies will become the most prevalent one for future commercialization. Currently the major obstacles towards wave energy commercialization are the high capital costs of wave energy devices (translated into high electricity unit costs for power generation) and the adverse working weather conditions that these devices have to endure, requiring additional safety features which results in escalation of the capital costs.

References

Adee, S. (2009). This Renewable Energy Source Is Swell - Oceanlinx begins building third-generation ocean-swell-to-energy generator. *IEEE Spectrum inside Technology*. Retrieved from http://spectrum.ieee.org/energy/renewables/this-renewable-energy-source-is-swell

Agarwal, A., Venugopal, V., & Harrison, G. P. (2013). The assessment of extreme wave analysis methods applied to potential marine energy sites using numerical model data. *Renewable and Sustainable Energy Reviews*, *27*, 244–257. doi:10.1016/j.rser.2013.06.049

Ahmed, M. R., Faizal, M., & Lee, Y. H. (2013). Optimization of blade curvature and inter-rotor spacing of Savonius rotors for maximum wave energy extraction. *Ocean Engineering*, *65*, 32–38. doi:10.1016/j.oceaneng.2013.02.005

Anbarsooz, M., Passandideh-Fard, M., & Moghiman, M. (2014). Numerical simulation of a submerged cylindrical wave energy converter. *Renewable Energy*, *64*, 132–143. Retrieved from http://www.sciencedirect.com/science/article/pii/S0960148113005867

Babarit, A. (2013). On the park effect in arrays of oscillating wave energy converters. *Renewable Energy*. doi:10.1016/j.renene.2013.03.008

Barbariol, F., Benetazzo, A., Carniel, S., & Sclavo, M. (2013). Improving the assessment of wave energy resources by means of coupled wave-ocean numerical modeling. *Renewable Energy*, *60*, 462–471. doi:10.1016/j.renene.2013.05.043

Borg, M., Collu, M., & Brennan, F. P. (2013). Use of a Wave Energy Converter as a Motion Suppression Device for Floating Wind Turbines. *Energy Procedia*, *35*, 223–233. doi:10.1016/j.egypro.2013.07.175

Bouali, B., & Larbi, S. (2013). Contribution to the Geometry Optimization of an Oscillating Water Column Wave Energy Converter. *Energy Procedia*, *36*, 565–573. doi:10.1016/j.egypro.2013.07.065

Clément, A., McCullen, P., Falcão, A., Fiorentino, A., Gardner, F., Hammarlund, K., … Thorpe, T. (2002). Wave energy in Europe: current status and perspectives. *Renewable and Sustainable Energy Reviews*, *6*(5), 405–431. doi:http://dx.doi.org/10.1016/S1364-0321(02)00009-6

CRES. (2002). *Wave energy utilization in Europe: Current status and perspectives*.

Dean, R. ., & Dalrymple, R. A. (1991). *Water wave mechanics for engineers and scientists - Advanced series on Ocean Engineering*. World Scientific.

Fadaeenejad, M., Shamsipour, R., Rokni, S. D., & Gomes, C. (2014). New approaches in harnessing wave energy: With special attention to small islands. *Renewable and Sustainable Energy Reviews*. doi:10.1016/j.rser.2013.08.077

Falcão, A. F. de O. (2010). Wave energy utilization: A review of the technologies. *Renewable and Sustainable Energy Reviews*. doi:10.1016/j.rser.2009.11.003

Goda, Y. (2000). *Random seas and design of maritime structures*. *Annals of Physics* (Vol. 15, p. 443). doi:10.1017/S0022112089222437

Guanche, R., Gómez, V., Vidal, C., & Eguinoa, I. (2013). Numerical analysis and performance optimization of a submerged wave energy point absorber. *Ocean Engineering*, *59*, 214–230. doi:10.1016/j.oceaneng.2012.10.016

He, F., Huang, Z., & Law, A. W. K. (2013). An experimental study of a floating breakwater with asymmetric pneumatic chambers for wave energy extraction. *Applied Energy*, *106*, 222–231. doi:10.1016/j.apenergy.2013.01.013

Heras-Saizarbitoria, I., Zamanillo, I., & Laskurain, I. (2013). Social acceptance of ocean wave energy: A case study of an OWC shoreline plant. *Renewable and Sustainable Energy Reviews*, *27*, 515–524. doi:10.1016/j.rser.2013.07.032

Jeans, T. L., Fagley, C., Siegel, S. G., & Seidel, J. (2013). Irregular deep ocean wave energy attenuation using a cycloidal wave energy converter. *International Journal of Marine Energy*, *1*, 16–32. doi:10.1016/j.ijome.2013.06.001

Korde, U. A., & Ertekin, R. C. (2014). On wave energy focusing and conversion in open water. *Renewable Energy*, *62*, 84–99. doi:10.1016/j.renene.2013.06.033

Leijon, M., Boström, C., Danielsson, O., Gustafsson, S., Haikonen, K., Langhamer, O., … Waters, R. (2008). Wave Energy from the North Sea: Experiences from the Lysekil Research Site. *Surveys in Geophysics*. doi:10.1007/s10712-008-9047-x

Leybourne, M., Batten, W. M. J., Bahaj, A. S., Minns, N., & O'Nians, J. (2014). Preliminary design of the OWEL wave energy converter pre-commercial demonstrator. *Renewable Energy*, *61*, 51–56. doi:10.1016/j.renene.2012.08.019

López, I., Andreu, J., Ceballos, S., Martínez De Alegría, I., & Kortabarria, I. (2013). Review of wave energy technologies and the necessary power-equipment. *Renewable and Sustainable Energy Reviews*. doi:10.1016/j.rser.2013.07.009

López, I., & Iglesias, G. (2014). Efficiency of OWC wave energy converters: A virtual laboratory. *Applied Ocean Research*, *44*, 63–70. doi:10.1016/j.apor.2013.11.001

Malara, G., & Arena, F. (2013). Analytical modelling of an U-Oscillating Water Column and performance in random waves. *Renewable Energy*, *60*, 116–126. doi:10.1016/j.renene.2013.04.016

Montoya Andrade, D.-E., de la Villa Jaén, A., & García Santana, A. (2014). Considering linear generator copper losses on model predictive control for a point absorber wave energy converter. *Energy Conversion and Management*, *78*, 173–183. doi:10.1016/j.enconman.2013.10.037

Nihoul, J. C. J. (1981). The dynamics of the upper ocean. *Dynamics of Atmospheres and Oceans*. doi:10.1016/0377-0265(81)90006-3

Poullikkas, A. (2009). *Introduction to power generation technologies*. New York: Nova Science Publishers.

Previsic, M., Bedard, R., & Hagerman, G. (2004). *E2I EPRI Assessment Offshore Wave Energy Conversion Devices. E2I EPRI WP – 004 – US – Rev 1* (pp. 1–52).

Simmonds, M. P., Brown, V. C., Eisfeld, S., & Lott, R. (2010). *Marine Renewable Energy Developments: benefits versus concerns*. *Renewable Energy*.

Smith, H. C. M., Haverson, D., & Smith, G. H. (2013). A wave energy resource assessment case study: Review, analysis and lessons learnt. *Renewable Energy*, *60*, 510–521. doi:10.1016/j.renene.2013.05.017

Stoutenburg, E. D., & Jacobson, M. Z. (2011). Reducing Offshore Transmission Requirements by Combining Offshore Wind and Wave Farms. *IEEE Journal of Oceanic Engineering*, *36*, 552–561. doi:10.1109/JOE.2011.2167198

Stoutenburg, E. D., Jenkins, N., & Jacobson, M. Z. (2010). Power output variations of co-located offshore wind turbines and wave energy converters in California. *Renewable Energy*, *35*(12), 2781–2791. doi:10.1016/j.renene.2010.04.033

Teillant, B., Costello, R., Weber, J., & Ringwood, J. (2012). Productivity and economic assessment of wave energy projects through operational simulations. *Renewable Energy*, *48*, 220–230. doi:10.1016/j.renene.2012.05.001

US Department of the Interior. (2006). *Technology white paper on the US outer continental shelf*.

www.altprofits.com. (2013). Business opportunities of wave energy devices. Retrieved from www.altprofits.com
www.aw-energy.com. (2013). WaveRoller. Retrieved from www.aw-energy.com
www.bwea.com. (2013). Wave energy projects. Retrieved from www.bwea.com
www.fujitaresearch.com. (2013). OWCs. Retrieved from www.fujitaresearch.com
www.pelamiswave.com. (2013). Pelamis project. Retrieved from www.pelamiswave.com