BALAZS CZECH and
PAVOL BAUER

Wave Energy Converter Concepts

Design Challenges and Classification

Digital Object Identifier 10.1109/MIE.2012.2193290
Date of publication: 15 June 2012

The utilization of renewable energy sources is a vital aspect for development of sustainability. Currently, an unexploited energy source is ocean waves. Various types of wave energy converters (WECs) are able to transform the motion of the waves into electricity. During the last 30 years, a wide range of prototypes was presented with different rates of success. The aim of this survey is to give an overview of how WECs are

1932-4529/12/$31.00©2012IEEE

categorized [operation principle and power takeoff (PTO) system] and show what are the most important criteria that have to be kept in mind when designing a WEC. A few important WECs are described and evaluated.

Ocean energy exists in different forms, including wave (kinetic and potential energy), current (kinetic energy of flowing ocean currents), tidal (from the rises and ebbs of tides), thermal (using the natural temperature gradient as a function of depth in tropical oceans), and salinity (chemical electric potential formed by the difference in salt concentration between freshwater and seawater) [1]. This article focuses on wave energy.

Because of the differential heating of the earth's surface by solar energy, winds are created. As winds blow over water, they create waves and transfer their energy into them. The amount of energy transferred depends on the wind speed, time applied, and distance covered. The world's potentially exploitable wave power resource should be in the order of 1 TW [2]. Like most forms of renewable energy sources, wave energy is distributed unevenly over the world (shown in Figure 1). Increased wave activity is found between the latitudes of approximately 30° and approximately 60° on both hemispheres, induced by the prevailing western winds blowing in these regions. The following regions offer the highest wave energy potentials over the globe: the Western European coast, the coasts of Canada and the United States, and the southwestern coasts of Australia, New Zealand, South America, and South Africa [4].

When comparing wave energy with other major renewable energy sources (wind energy and photovoltaics), its biggest advantage is that it offers the highest energy density (see Table 1). Also, an important factor is that they represent a more constant and predictable energy source. Compared with the aforementioned renewable energy sources, the negative environmental impact is also noticeably less for wave energy. In addition, waves have a unique feature, i.e., they can travel large distances with little energy loss (if they do not encounter head winds) [5].

The devices that try to capture the energy within the waves and transform it to electricity are called WECs. Over the last 30 years, extensive research has been done to develop WECs, which are concluded in several surveys [5]–[12]. Thousands of WEC concepts have been patented [12], but they are relatively immature compared with other renewable energy technologies. There have been several government-sponsored programs and industry lead projects, particularly in the United Kingdom, Ireland, Portugal, Denmark, Norway, and the United States [6], [12]–[21], to fund the research.

Design Challenges

To be able to exploit the energy from the waves, several challenges need to be tackled to successfully create a reliable machine that is economically viable at the same time.

- Because of irregularity in wave amplitude, phase, and direction, the device needs to be tuned to the resource to be able to operate efficiently. The biggest difficulty is to obtain high energy conversion efficiency over an entire range of excitation parameters [5].
- The loading on the WEC can be 100 times higher than the average loading in extreme weather

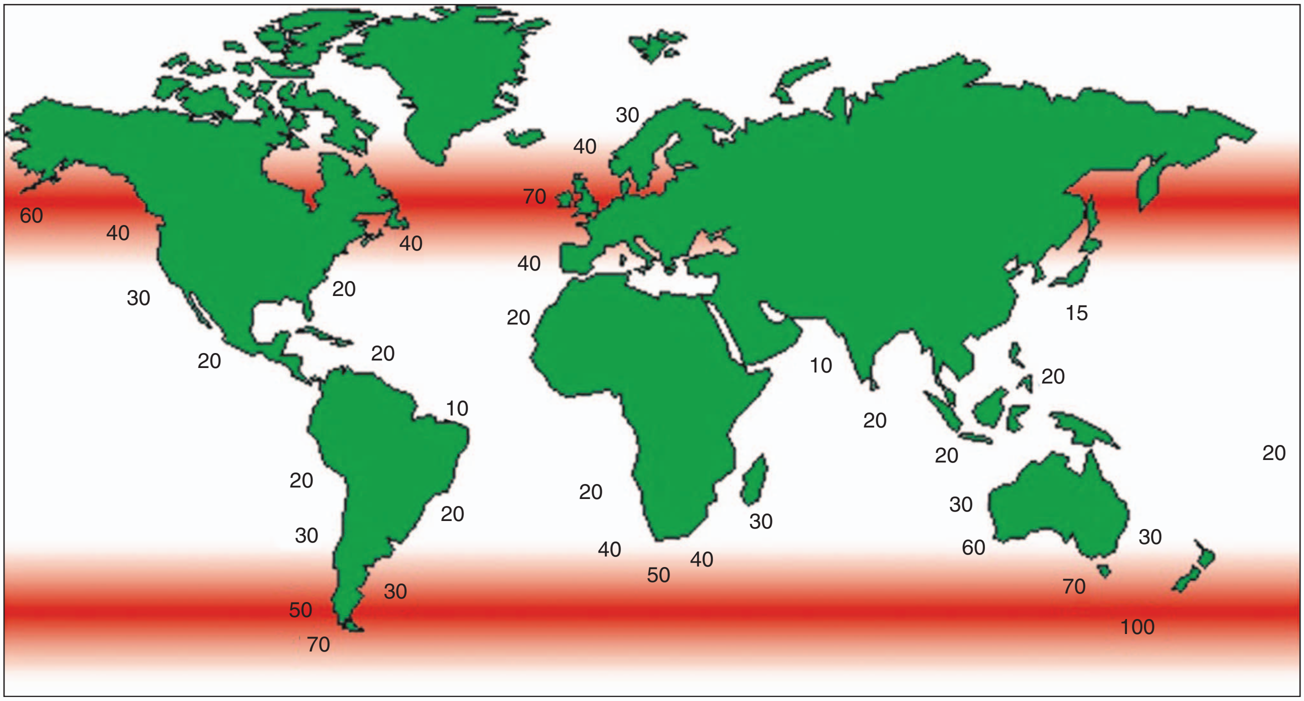

FIGURE 1 – Global wave power distribution in kilowatt/meter of crest length. (Figure used with permission from [1].)

TABLE 1–WAVE ENERGY COMPARED WITH OTHER RENEWABLE ENERGY SOURCES [6].

	PHOTOVOLTAIC	WIND	WAVE
Status	Early commercial	Commercial	Precommercial
Energy source	Sun	Sun	Sun–wind
Power density	1 kW/m^2 at peak solar isolation	1 kW/m^2 at 12 m/s [General Electric (GE) 1.5-MW machine]	25 kW/m at San Francisco, average annual power flux
Variability	Daily cycles—clouds	When it blows	24$\times$7 and highly variable
Predictability	Poor	Hours	Daily

conditions (e.g., storms). Thus, the WEC needs to be over-dimensioned to withstand these severe conditions, which highly increase the price of the device. However, the generated revenue by the WEC is based on nominal operating conditions, where the price of the WEC structure is cheaper. This creates a major design problem and could make the WEC an economic failure [7].

- A major challenge is the coupling of the irregular, slow (frequency 0.1 Hz) motion to drive a generator with an output quality acceptable to the utility network [12]. There are several ways to overcome this problem: implement an energy storage system inside the device based on the WEC operating principle [e.g., the water stored in the water reservoirs on the top of overtopping devices (OTDs) can be used as an energy buffer, using hydraulic accumulators in a hydraulic PTO] or use a standard external energy storage unit, which could be fuel cells, superconducting magnetic energy storages, energy storage in supercapacitors, and battery storage [57], [59]. Another option is to connect the devices in an array to smooth the power [59].
- To create a successful converter, the device needs vigorous testing and evaluation procedures to be undertaken because, in most cases, the inventors of the WECs do not have extensive knowledge and the necessary experience in operating offshore devices and equipment. In [60], the reliability testing of WEC components is investigated. A case study of a hydraulic WEC is introduced in [61], where the following subsystems of the WEC are considered: mooring, structure, six PTO (in parallel), and power transmission. The results of the study show that, after 6,000 h of operation, the WEC has higher maximum 15% reliability in any case. However, these unfavorable results are due to prototype device, outdated/pessimistic and often generic failure rate data, no repair activities considered within 12 months time, and crude adjustments.

Classification

The classification of WEC can be done in many ways, but there are four categories that are commonly used today [7]. These are explained in the following subsections.

Classification According to Operation Principle

Oscillating Water Column

WECs extract the energy from a bidirectional airflow generated by the oscillating sea-level chamber. The device's chamber is filled with air and seawater. Through an underwater opening to the sea, the waves change the level of the seawater inside the chamber. This causes the volume of the air inside the chamber to change: it gets compressed as the incident wave makes the free surface of the water rise inside the chamber and decompresses as the waves leave. The compressed air leaves through an aperture above the water column and makes a turbine running. When the seawater leaves the WEC, this cycle repeats itself with a different direction, generating a bidirectional airflow in one cycle [10].

Overtopping Device

These devices rely on the physical capture of water from waves. The incoming waves overtop the edge of the WEC and will be held in the reservoir a few meters above sea level. From the reservoir, the water is returned to the sea through low-head turbines, which are responsible for generating electricity. An OTD may use collectors to concentrate the incoming waves and increase the wave height to increase the amount of energy captured by the WEC [3].

Wave-Activated Bodies (WABs)

The WEC's body is made from several units that are able to move and oscillate around a reference point (this can be a fixed point or another body part). As the device is placed in the water, the waves start to excite the system. The energy is extracted from the relative motion of the bodies or the motion of one body relative to its fixed reference point. The WEC movement or motion can be primarily described as pitch, heave, and roll [22].

Classification According to Location

The shoreline converters are located at the shore. The devices can be placed on bottom of the sea in shallow water, integrated in breakwater-like structures, or fixed to a rocky cliff, which have the advantage of easier maintenance and/or installation. Moreover, they do not require mooring and long lengths of underwater sea cable to connect the WEC to the grid. However, the waves at the shore contain less energy, and the lack of suitable land sites also causes difficulties for these systems. Environmental problems could also arise, because the shore of the sea is reshaped [5].

The nearshore converters are installed in moderate water depths, where shallow water conditions are still satisfied. They are usually located hundreds of meters from the shore, but it can even be a few kilometers away. Usually, they are fixed to the sea bottom to be able to harvest most of the energy that the waves possess and to avoid mooring. However, this also has disadvantages: the structure needs to bear the stress that arises when the waves pass over it and the cost of the single unit [10].

The offshore converters are floating or submerged devices in deep waters, moored to the sea floor. These WECs represent the most promising class of WECs. They may exploit the vast wave potential of the open seas before energy dissipation effects can take place. Because of the open sea, survivability represents a big problem for these devices, and the structure has to bear exceptionally high loads. High reliability is required to avoid excessive maintenance-related costs. The long length of underwater sea cables is used to deliver the power to the grid [4].

Figure 2 shows a classification example of WECs based on the previous two points.

Classification According to Power Takeoff System

The three most used types of PTO systems are air turbines, linear generators, and hydraulic systems. There are also alternative ways to produce electricity, which were implemented in some unique WEC configurations [e.g., electroactive polymers (EAPs)].

In an oscillating water column (OWC), the PTO system consists of a self-rectifying axial-flow air turbine, located in a duct connecting the air chamber with outside atmosphere. Extracting energy from the airflow is more advantageous because the airflow rate is higher than the slow velocities of waves, and therefore, it is easier to couple to a generator. A self-rectifying turbine has the capability to operate without a system of self-rectifying valves, accepting a bidirectional airflow while rotating in the same direction always. It is usually connected to a variable-speed generator. The most critical element in the energy conversion process is the turbine itself, making it essential to optimize its performance, especially from the price point of view. The two most commonly used air turbines in OWC converters are the Wells turbine and the impulse turbine. The Wells turbine [23], [24] is used in a low-pressure environment to avoid rectifying the air stream by expensive technologies. The biggest advantage of this type is that it is bidirectional; although the direction of the air stream is changing, it still keeps the rotation of the turbine shaft in the same way. However, this also has its flaws in reaching the bidirectional usage; the airfoil of the turbine blades needs to be symmetric, which leads to an efficiency drop during conversion. This occurs because symmetric airfoils have higher drag coefficients than the asymmetric ones that they use during constant air stream direction. Also, as a result of the asymmetric air foil, at certain cases, flow separation occurs. The turbine will stall, and, in severe cases, the driving torque would become negative. Another disadvantage is that it needs a motor or generator for start-up and has a relatively large size compared with its power level. The impulse turbines [25], [26] are self-pitched, controlled turbines with guided vanes. A set of guide vanes can be found on each side of the rotor. These guide vanes are pivoted, and they can freely rotate between the two given angles, which are determined by mechanical configuration. When the airflow changes direction, the guide vanes also flip and orient themselves to the right position (in upstream guide, they act as a nozzle, while in downstream, they act as a diffuser). As a result of this design, they are stall free. They are self-starting as well, but it is more complex in design than the Wells turbine as it needs the

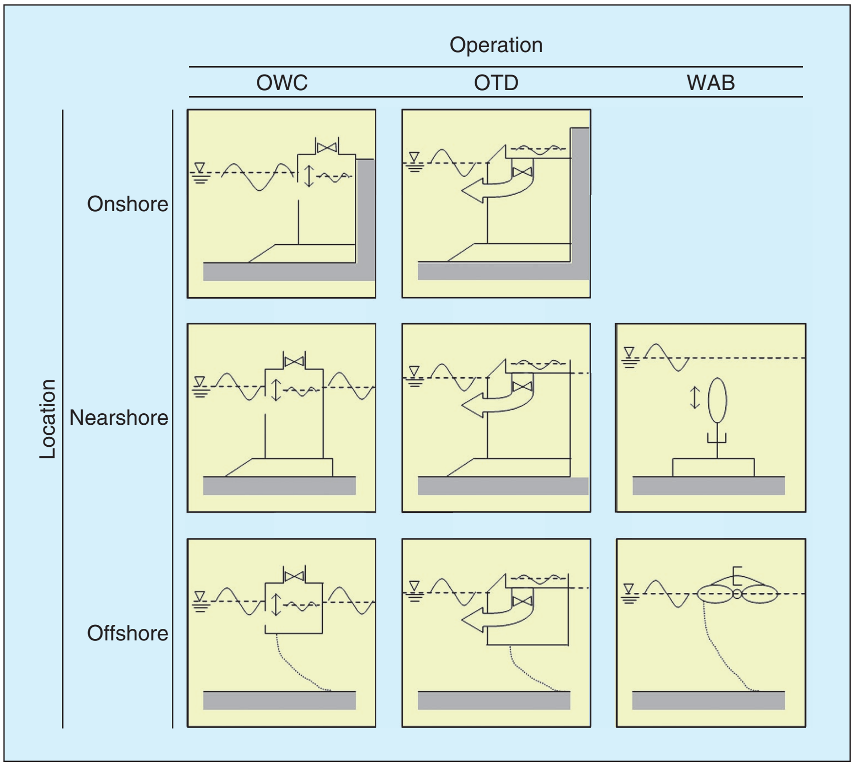

FIGURE 2 – WEC classification according to principle and location. (Figure used with permission from [22].)

guide vanes to operate. When comparing the efficiency of two turbine systems, it can be seen that the impulse turbine has a far better range of efficient operation than the Wells turbine. On the other hand, at optimal operating point, the Wells turbine has considerably higher efficiency. Because of the wider range of operation, the impulse turbine can also run at lower rotational speed [7], [27].

It is also possible to convert the motions of sea waves with the help of hydraulic systems [7], [28]. These systems are able to handle large forces at slow speeds, which is remarkably small and light weighted. Traditional hydraulic systems use coupled variable displacement pumps and motors. At their ideal operating point, their peak efficiency is around 80%. However, away from this ideal operating point, the efficiency suffers a drop, which can become less than 60% as the losses increase (leakage, coulomb and viscous friction, and compressibility). By integrating hydraulic accumulators into the system, the PTO will be able to smooth out the irregularities in the incident power fluctuations. Unfortunately, most of the devices with hydraulic PTOs are located offshore, which raises problems. Even with thorough preparations (the pipes must be filled up with the hydraulic oil completely so that no air bubbles are left in the system and the seals are checked), the system often suffers breakdowns: the hydraulic houses tend to fail too often and hydraulic connectors leak too easily. This significantly decreases the uptime of the system and makes it unreliable. Moreover, in case of offshore devices, the maintenance is quite problematic and expensive as well.

In case of direct-drive WECs where the moving part of a WEC is coupled directly to the PTO, a linear generator [29], [30] can be used. A linear generator produces electricity directly from the linear movement between the fixed stator—which contains the armature windings—and the moving translator, where magnets are mounted with alternating polarity. A physical gap between the translator and the stator is called the air gap. A voltage is induced in the windings as the magnetic field changes due to translator motion in accordance with Faraday's law. The most important factors for these devices are damping (the whole system is an oscillating one, which means that the waves are acting as a driving force, while the generator acts as a damper, and the absorbed energy strongly depends on the damper), reaction force (because of the direct drive, the generator moves slowly, and to get the same output power, the reaction force needs to be big), overloads (the incoming waves are continuously varying, their speed is different, and consequently, the generator produces varying power, and it is needed to take the extreme values into account), stroke length (should be set according to the wave heights), and the grid connection (to connect to the commercial grid, the voltage level needs to be set, the current needs to be rectified, and the frequency changed). Compared with the other PTOs, it is capable to convert the mechanical energy straight to electrical energy and still has reasonable efficiency. It is also simpler than the other systems and requires less maintenance. However, they are rather expensive although the cost of the magnets has deceased recently, which makes this type of PTO a viable economic option. Figure 3 shows the most frequent PTOs in WECs.

Classification According to Directional Characteristics

Point Absorber

Point absorber is a kind of converter that is either floating or mounted on the seabed and absorbs energy in all directions through its movements at/near the water surface. It usually provides a heave motion that is converted by mechanical and/or hydraulic systems in linear or rotational motion for driving electrical generators. The horizontal physical dimensions of the device are much smaller than the wavelength of the waves [7].

Terminator

A terminator is a near-surface floating structure similar to a point absorber, but absorbs energy in only one direction. The device extends perpendicular to the wave direction, restraining and terminating the waves as they arrive. Applying resonance greatly

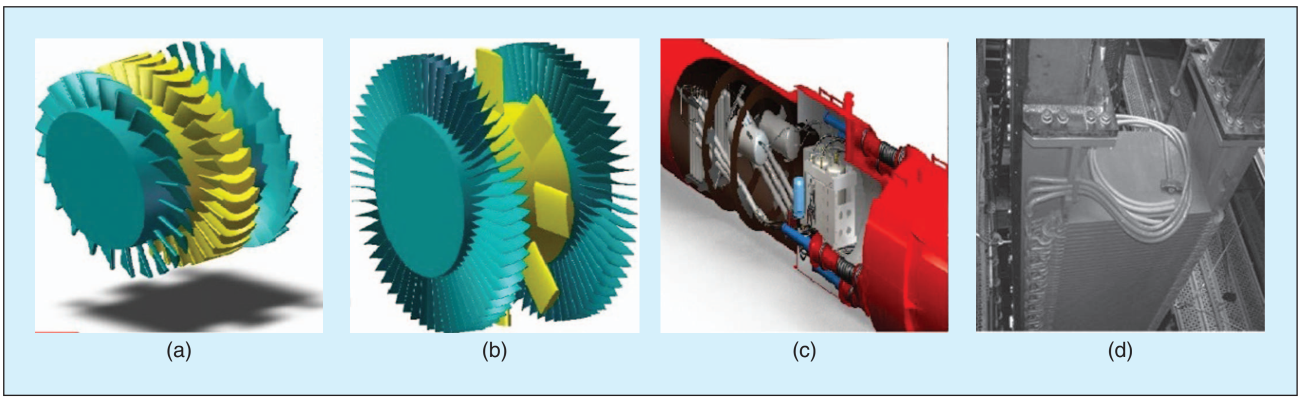

FIGURE 3 – The PTOs for WECs: (a) Wells turbine [62], (b) impulse turbine [62], (c) hydraulic system [28] (photo courtesy of Pelamis Wave Power), and (d) linear generator [31].

increases the energy capture. Hence, a PTO system may take a variety of forms [10].

Attenuator

An attenuator is a long, floating WEC aligned in parallel with wave direction, which effectively rides the waves. Movements along its length can be selectively constrained to produce energy. It has a lower area perpendicular to the waves compared to a terminator so that the device experiences lower forces [9].

Devices

Currently, the number of existing wave energy companies can reach up to 100, and there are even more WECs. A list of the existing technologies and the leading companies can be found in [32]. Here, only a few important devices will be introduced.

LIMPET

The land-installed marine-powered energy transformer (LIMPET) is a shoreline-based OWC located on Islay Island (United Kingdom). It was developed by the Queen's University of Belfast and Wavegen of Inverness from 1998 to 2000 [12].

Structure

As every OWC, the design is based on the air chamber where the sea level can oscillate (Figure 4 illustrates the device). This oscillation creates a bidirectional airflow, which drives an air turbine. To reach optimal overall conversion efficiency, the width of LIMPET was selected as 21 m based on the wave conditions at the Islay Island. However, the water plane had to be divided into three side-by-side water columns for two reasons. First, if the width of the column is too high, there is an increasing risk of transverse wave excitation within the water column, which will reduce the energy capture ability of the device. Second, the roof required to span the 21-m width of the column without additional support is too large to be economically viable. To create the additional support, the chamber got divided. The column bears a resemblance to slipway with a 40° angle to the horizontal [11], [33].

PTO

A pair of 250-kW bidirectional Wells turbine was placed inside the LIMPET. Each turbine has seven blades of 2.6 m diameter, and they have symmetrical airfoil section. The blades are bolted via a containment ring (that carries the centrifugal loads) to a plate, which is attached directly to the generator shaft. In the baseline configuration of the LIMPET plant, two of these assemblies are used in a back-to-back (B2B) configuration to form a contrarotating biplane turbine [33].

The average wave power level at the Islay site is around 20 kW/m. At this location, the device is estimated to have an average electrical output of 206 kW, amounting to 1,800 MWh/year [11].

Price

This is site specific, based mostly on the steel–concrete structure of the device. According to [11], the shoreline OWC cost, typically 60–75%, is associated with a robust structure. In case of the LIMPET, there was a large degree of uncertainty in estimating the cost, because of the lack of detailed information and was only meant to be a pilot plant; however, it is believed to be in the range €1.1 million [34]. The annual operation and maintenance costs were estimated to be approximately €25,000. The system was being developed with a perspective to be maintained at remote locations by qualified staff [33].

Current State

The plant has been in operation since 2000 (from the time it was built). The availability of the WEC has improved dramatically since the first year of operation: it has exceeded 90% between 2005 and 2009, while in 2010, it was running at 98%. The plant has accumulated more than 60,000 grid-connected generating hours [35].

Pelamis

The Pelamis device is a semisubmerged, articulated structure composed of cylindrical sections linked by hinged joints. The floating system is moored to the sea bottom through a complicated mooring system to hold the Pelamis in one place, but it would let the device self-align itself to the incoming waves. From the wave-induced motion of the hinged joints (shown in Figure 5), the hydraulic PTO extracts the power and transfers electricity to the grid [8], [12]. The world's first commercial wave farm was created from three 750-kW Pelamis device in 2008, 5-km offshore from Póvoa de Varzim in Portugal [28], [37].

Structure

The prototype machine consists of four semisubmerged iron cylinders with a diameter of 3.5 m and length of 30 m.

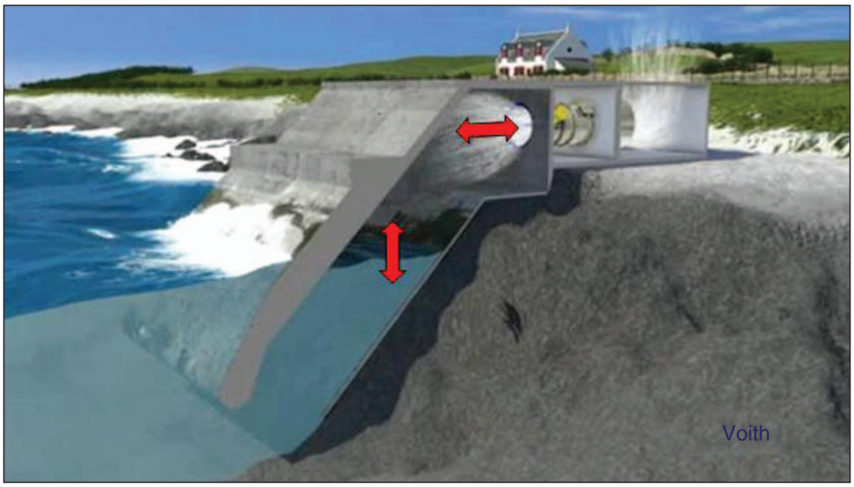

FIGURE 4 – A schematic drawing of the LIMPET OWC [3]. (Figure courtesy of Voith Hydro Wavegen Limited.)

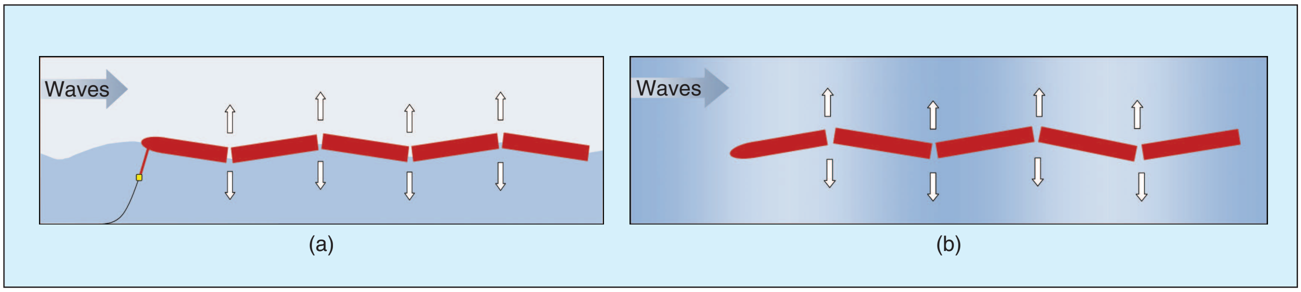

FIGURE 5 – Illustrating the wave-induced motion of the Pelamis WEC [28]. (Figure courtesy of Pelamis Wave Power.)

These are called as floaters. Between two neighboring floaters, there is a power conversion module (PCM). The floaters and the PCM are connected through hinged joints, which have two degrees of freedom. The PCM has the same diameter as the floater, but their lengths are only 5 m. These units contain the PTO; thus, they are responsible for electricity production.

The articulated structure is 135 m in total length, and two thirds of it is installed semisubmerged offshore in deep waters. With the help of joints, the system can be tuned to the sea wave's wavelength; thus, it can enter resonance and oscillate with the highest amplitude to extract maximum energy from the waves [36], [37].

PTO

According to [7], the prototype's PTO unit can be divided into two separate parts, which can be referred to as primary and secondary transmission through high-pressure accumulators.

The primary transmission consists of hydraulic cylinders and their controls. It converts the work done by the waves on the structure and transmits the energy to the accumulators, where it is temporally stored. The chambers in the hydraulic cylinders are opened and closed by electronic valves. Each PCM is connected with three heave joints and three sway joints, which allows different control strategies in each wave cycle to maximize energy capture. They determine the reaction torque at the joints and can thus be varied through a range of values depending on the accumulator pressure and the number of cylinder chambers that are connected. The accumulator pressure is determined by difference of the primary transmission energy intake and the secondary transmission outlet. The secondary transmission contains hydraulic motors that are coupled to a three-phase asynchronous generator with a rated output of 125 kW. Its task is to convert the stored energy in the hydraulic accumulators into electricity. The generators are designed based on Lafert's standard AM 315 asynchronous electric motor (AEM). They can run up to an operating speed as those of electric motors, and thus, they are able to avoid synchronization; however, as synchronous speed is reached, a positive torque is applied by the attached hydraulic motor that forces the machine into generation mode. Each PCM holds two PTO circuits, and altogether, there are three PCMs in WEC; thus, the whole system is rated for 750 kW. Each of the three asynchronous generators is connected to a common 690 V, three-phase bus cable, which runs along the length of the device. At the end of the device, a single 950-kVA transformer is used to step up the voltage to an appropriate level for transmission to shore. The produced high-voltage (HV) power is fed to the seabed by a single flexible umbilical cable, and then, either it is transmitted directly to the shore via a conventional subsea cable or connected to a substation in a wave farm [37]. An oil-to-water heat exchanger is integrated in the PCM to dump surplus power in large seas and in case of grid failure to provide the necessary thermal load [7].

Based on [28], the primary circuit efficiency can reach 94%, while the secondary transmission can operate with an efficiency of 80% over a representative range of conditions.

Cost

To estimate the levelized production cost of the electricity produced by Pelamis WECs, feasibility studies were made [38]. For these studies, the prototype machine was replaced by an envisioned commercial device, whose price was assumed to be US$2–3 million. The commercial WEC was only rated for 500 kW (to harmonize with the wave climates); however, because of the change in the mooring configuration, the unit performance still increased by 27%. The availability for the devices was chosen as 95% while the system efficiency for power conversion was set to 88%. The aim of the study is to generate 300,000-MWh electrical output annually for 20 years at five different locations in the United States: Hawaii (HAW), Oregon (ORE), California (CAL), Massachusetts (MAS), and Maine (MAI). Taking these parameters into account, the results are summarized in Table 2. It is shown that electricity can be produced around US$0.10/kWh (in case of MAI, the cost of electricity is significantly higher, and thus, at that location it is not economically viable).

Current State

The machines in Póvoa de Varzim broke down during operation and were towed back to harbor in 2008. Because of the financial crisis, the ownership of the project changed, slowing down developments. Currently, the second generations of the devices (P2) are being developed (upgraded version of the previously introduced prototype), while they are planning to open new wave farms with increased capacity [39].

Wave Dragon

Wave Dragon is an offshore OTD, which was invented by Friis-Madsen, Löwenmark F.R.I Consulting Engineers, in 1999. The front face of the device is a curved ramp, where the oncoming waves surge up into the reservoir. To increase the power of the machine, it uses long reflector wings: it amplifies the waves that get between the reflectors and leads them toward the front of the device. Behind the ramp lies the reservoir that gathers water. The energy is extracted as the water drains back to the sea through low-head hydroturbines within the reservoir. This procedure is illustrated in Figure 6. This offshore terminator needs to be placed in water deeper than 20 m. It has a one-step conversion system, yielding to a very simple construction and has only the turbines and wave reflectors as moving parts. Each unit can have a rated power of 4–7 MW depending on the wave climate at the deployment site [7], [8].

TABLE 2–ESTIMATED PERFORMANCE AND PRICE OF ELECTRICITY FOR COMMERCIAL PELAMIS WAVE FARMS IN THE UNITED STATES [38].

	HAW	ORE	CAL	MAS	MAI
Average annual wave power flux (kW/m)	15.2	21.2	11.2	13.8	4.9
Depth (m)	60	60	30	60	60
Distance from the shore (km)	2	3.5	13	9	9
Annual energy absorbed (MWh/year)	1,989	1,997	1,683	1,738	584
Annual energy produced (MWh/year)	1,663	1,669	1,407	1,453	488
Average electrical power at bus bar (kW)	191	191	161	166	56
Number of Pelamis units needed	180	180	213	206	615
Total plant investment (US$million)	270	235	279	273	735
Annual operation and maintenance cost (US$million)	11	11	13	12	33
Ten-year refit cost (US$million)	24	23	23	26	74
Fixed charge rate	9.2	9.2	9.2	9.2	9.2
Cost of electricity (US$/kWh)	0.10	0.09	0.11	0.11	0.32

Structure

According to various sources [40]–[44], the Wave Dragon can be divided into four main elements (which can be seen in Figure 7).

- The first element is the main body, which is basically a large floating reservoir. To ensure stable electricity production, the pitching and rolling motion needs to be reduced; thus, the WEC needs to be heavy and large. By the built-in air chambers, the Wave dragon can be tuned to the wave climate: by controlling the pressure inside air chambers, the floating height of WEC is adjusted to the incoming wave heights. Using such a huge main structure, the terminator will have a very broad bandwidth; thus, its performance would not depend on rapid tunability.
- The second element is the two-patented wave reflectors focusing the waves toward the double-curved ramp linked to the main structure. The wave reflectors have the verified effect of increasing the significant wave height substantially and thereby increasing energy capture by 70% in typical wave conditions.
- The third element is the PTO, which is located in the main structure.
- The fourth element is a slack catenary mooring system, which ensures that the Wave Dragon is connected to the seabed. It enables the device to maximize the energy capture: it lets the device floating, while it turns the device into the wave direction.

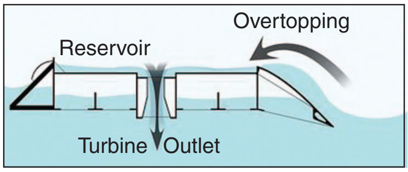

FIGURE 6 – The basic principle of the Wave Dragon [41]. (Figure courtesy of Wave Dragon ApS.)

FIGURE 7 – The main elements of the Wave Dragon [41]. (Figure courtesy of Wave Dragon ApS.)

PTO

The low-head turbines in the main structure extract the potential energy from water, which runs down from the reservoir to the sea. The hydraulic efficiency of the turbine is 92% in the relevant head and flow ranges. There are many challenges facing to design suitable low-head turbines [41].

- The turbines have to operate at very low-head values, ranging from 0.4 to 4.0 m, creating an exceptionally wide variation.
- They have to work from zero to full load frequently because of the wave distribution.
- The turbines have to operate in a very hostile environment, with only a minimum of maintenance being possible.

In [44], it is stated that efficient operation over the wide discharge range is ensured by using 16 relatively small turbines that can be switched on and off individually rather than a few large turbines. To grant a high efficiency throughout the wide-head range, the turbines are operated at variable speed and directly coupled to a generator. Three types of generators were compared for the Wave Dragon: a low-speed permanent magnet synchronous machine (PMSM) and a low-speed squirrel cage induction machine (SCIM) with or without a gearbox. It was concluded that an SCIM is the most advantageous solution with a B2B (ac–dc–ac) converter, but PMSM offers attractive solution for future devices [46]. By assigning a B2B converter to the generator, the variable speed operation mode is solved; moreover, a very flexible power conditioning is reached. The proposed structure is a standard converter for variable speed applications (e.g., wind turbines); thus, it is cost effective [47]. The PTO's schematic drawing can be seen in Figure 8.

The 7-MW prototype device in Nissum Bredning was connected to a grid, via a transformer, which steps up the voltage from 690-V_{rms} converter output to 11-kV cable voltage, and a 5-km long submarine cable [45]. Because of the long cable and its inherent phase shift, a parameter estimation of the grid is desirable. By applying a harmonic compensator, sinusoidal currents can be fed to a distorted grid. However, this method suffers difficulties in real world: estimating the grid impedance by a step response leads to inaccuracies in case of reactive power conditions [48].

Cost

A full-scale prototype will cost approximately €11 million and will have an estimated production price of €0.11/kWh [40]. It needs to be pointed out that such a device is a relatively inefficient wave power absorber when it is taken into account that how much material is required to absorb a certain amount of power. It can cause a problem in the device's long-term economic competitiveness (to some extent, the reflector arms can make up for this shortfall [6].

Current State

Successful one-fourth model tests were carried out in Nissum Bredning in 2004. A full-scale model was scheduled to be set up in Wells in 2008; however, because of the financial crisis, the project was pushed back significantly, i.e., due to lack of funding [45].

Archimedes Wave Swing

The Archimedes wave swing (AWS) converter was developed by the Dutch company Teamwork Technology in 1993 [3]. AWS is an offshore point absorber originally equipped with a linear generator as a PTO. It is a unique wave energy conversion system because it is completely submerged. This is vital in the survival of WEC, since this makes it more robust and significantly increases its chances to survive storms. Also, it is not visible to the observers, creating a more friendly public profile [31].

Structure

Basically, AWS is an air-filled cylindrical steel chamber whose lid, the floater, is a vertically moving body, while the bottom part, the silo, is fixed. The converter is driven by the fluctuations of pressure caused by the surface waves (see Figure 9). When the crest is above the AWS, the volume of the chamber is reduced because of the pressure that arises from the extra water. An opposing phenomena happens when a trough is above the converter, the pressure of the water column will be smaller than the pressure inside the chamber; for this reason, the lid of the chamber will go up and the volume of the chamber will increase [30].

PTO

The air within the chamber behaves like a spring whose stiffness can be adjusted by pumping the water in or out of the chamber. In case the height of the waves exceeds the limit for the device, water brakes are activated to decrease the wave force acting on the system. These actions of the water brakes together with the generator provide damping. The maximum energy can be extracted when the device is tuned in resonance with the waves. A direct-drive, permanent magnet linear synchronous (PMSL) generator is used for energy conversion. The PMSL generator consists of two double-sided stators and four translators. The main reasons for choosing a PMSL generator are its high force density, reasonable efficiency at low speeds, cheaper magnet prices, and no contact with the translator [7]. In the prototype device, the generator is connected to a current source inverter (CSI) [49]. CSI was chosen over voltage source inverter (VSI) to control the converter as the exact position of the translator is not needed, it was cheaper than a VSI converter, and it was estimated that it has lower conduction losses and lower switching losses [31]. However, for future devices, a B2B VSI is advised because the power factor at the grid side can be controlled, the grid currents can be

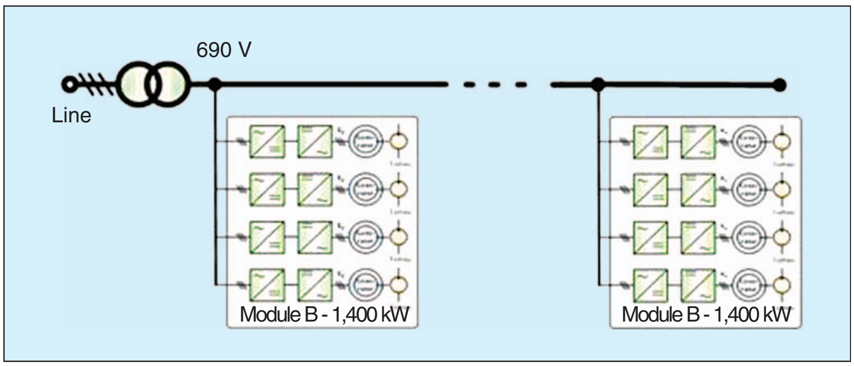

FIGURE 8 – The PTO of the Wave Dragon [47].

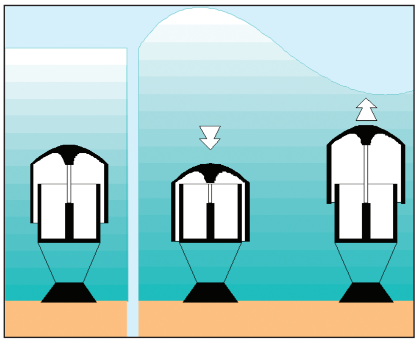

FIGURE 9 – The operating principle of the AWS. (Figure used with permission from [31].)

made sinusoidal, and the generator force can be larger; thus, the annual energy yield will increase by almost 20%, and the generator power factor can be controlled to minimize the generator and cable losses. In the prototype, the maximum peak power was 2 MW while the maximum average power was 1 MW [31]. By applying the B2B VSI converters, the fluctuating power of the AWS can be converted into controlled electric power and transmitted to the shore with appropriate voltage and frequency. Several topologies were developed to create wave farms [50]. The parameters of the individual park components were selected from standard components, the power flow process was modeled, and economic calculations were derived. The park topologies were compared from the point of view of annual energy yield, yearly losses, price, and levelized production cost.

Cost

There is no official data about the price of the prototype. According to [50], the levelized production of electricity for 45-MW average power wave farm can be as low as €0.03/kWh if only the transmission system price is accounted for.

Current State

The prototype of the AWS I was submerged and tested in 2004 on the northern coast of Portugal (Figure 10). However, during the end of testing, a severe failure occurred, and the device sank. Since then, the company moved to Scotland and is currently developing the third generation of the AWS device. This device is completely different than the prototype: the linear magnet generator was replaced by a hydraulic/pneumatic PTO, and the power rating of the device was increased considerably.

Navigation Buoy with Electroactive Polymer PTO

Dielectic elastomers (DEs) are a special type of electroactive polymers. From an electrical point of view, these type of materials form a parallel plate capacitor: the compliant electrodes are the infinitely long plates, while the polymer is the dielectric medium between the plates. If the material is subjected to deformation, the area and thickness of capacitor changes which will cause the capacitance to vary as well. By precise charging and discharging energy can be harvested from the varying capacitance. In case of wave energy application, the challenge is to successfully design a WEC with an DE PTO [52]. Researchers at SRI and Hyperdrive created a buoy type point absorber with DE PTO in 2007.

Structure

The buoy is similar to navigation buoy. The flotation ring of the buoy has a donut shape of 2.5 m in diameter. The total height is 3 m above the water line. The DE generator unit was set at the center of the buoy [53]. It is shown in Figure 11.

PTO

This DE generator prototype is a device that is designed to provide onboard power for navigation buoys. The PTO has a cylindrical shape with a diameter of 40 cm and height of 1.2 m. Two polymer rolls were installed into the PTO module. Each roll had a diameter of 30 cm with a length of 20 cm and weighed 150 g (active length of DE in the stretched condition).

Examples for the charging/discharging circuit are given in [54] and [56]. These circuits have special requirements: the elastomer needs to be charged to a very high voltage (several kV), its capacitance is very low, while it acts a continuously changing source which requires a wide operation range from the converter and at the same time high efficiency at the various operating points. Based on control the circuits can be divided into two groups: passive and active. The passive control circuits include charge pumps, diode

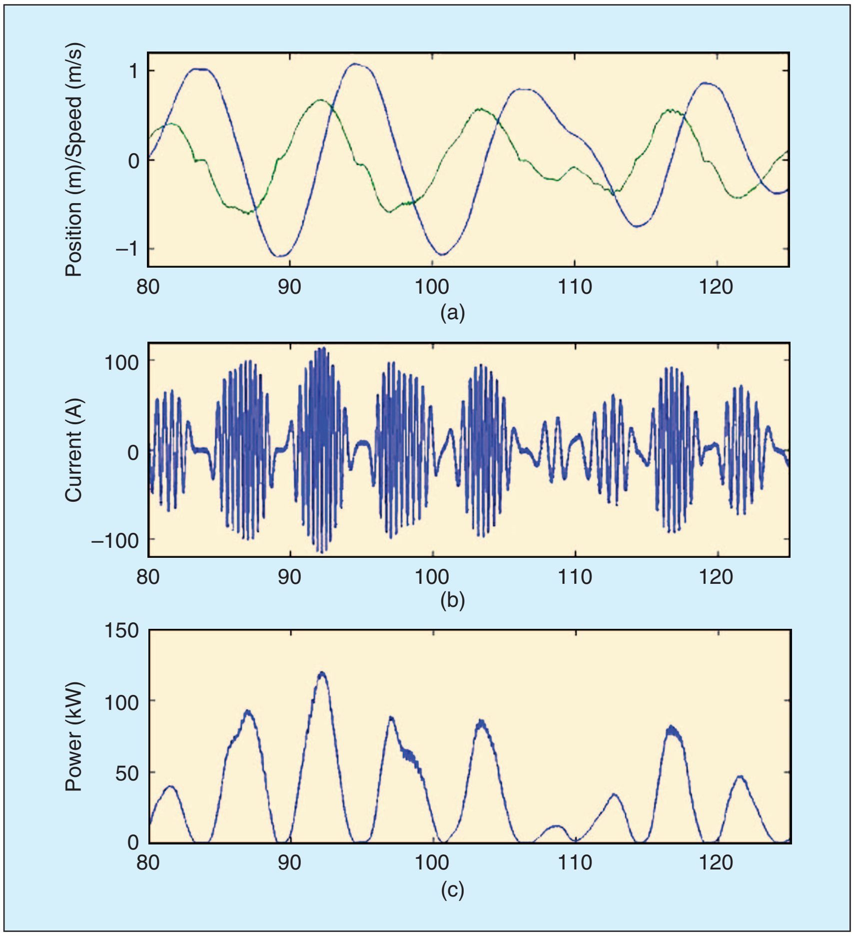

FIGURE 10 – The (a) measured position, (b) phase current, and (c) output power during the first tests of the AWS. (Figure used with permission from [31].)

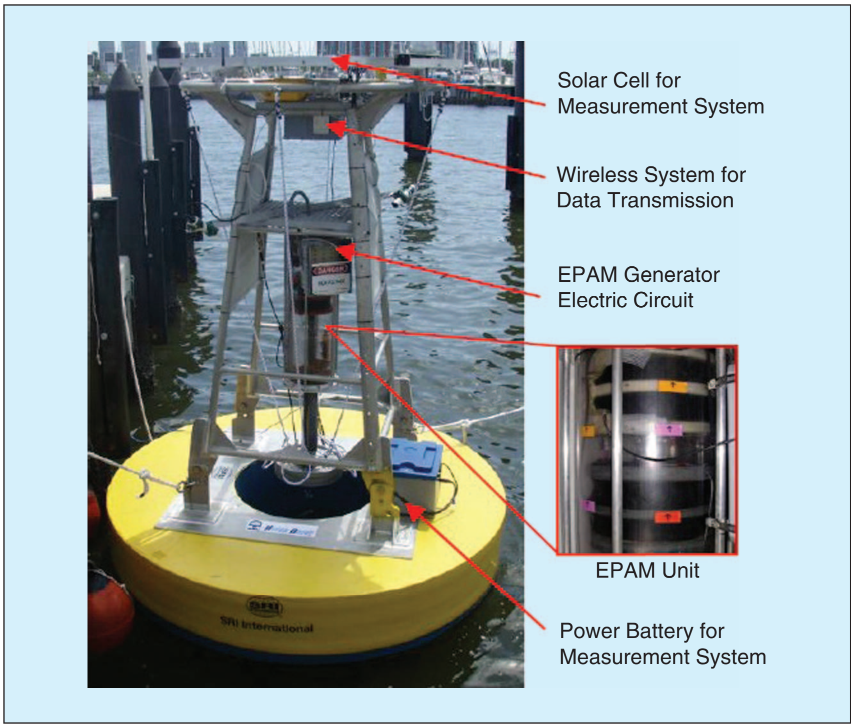

FIGURE 11 – An EPAM buoy prototype. (Figure used with permission from [53].)

rectifiers, etc., which are robust, simple, cheap, require no active components and control, but on the other hand can't maximize the potential of the elastomer, can't harvest the maximum amount of energy in the charging/discharging cycle. By applying active control, the circuits become more complex, more expensive, while the reliability of the system will decrease, but on the other hand by applying a proper charging/discharging strategy, the harvested energy from the elastomer can be significantly increased. In [52] three different (constant voltage, constant charge and constant electric field) energy harvesting strategies are introduced to withdraw energy from the polymer. They have been compared and as expected, the constant field cycle had the largest energy gain. The most notable limiting factors, such as parasitics of the circuit and the material, converter efficiency, residual charge level and current waveform has been discussed and their effect on the energy harvesting analyzed. Noting these limitations a novel constant field harvesting cycle has been proposed and optimized to maximize the energy gain. By obtaining this optimized innovative current waveform (illustrated in Figure 12), a suitable power electronics converter can be designed. The active converter can be boost, buck converters, flyback converter, full bridge push-pull converter topology using a transformer, multilevel converters, etc.

During testing, the waves at the installed location were only in the order of a few centimeters in height, which are extremely severe conditions for this type of experiment. However, when waves of several centimeters in height approached the buoy, a maximum of 1.2 W of electric energy was harvested. During the test conditions, the bias voltage was approximately 1,800 V, but if the bias voltage was increased to 5,000 V, a maximum electric energy of 11 W could have been obtained under the same conditions [55].

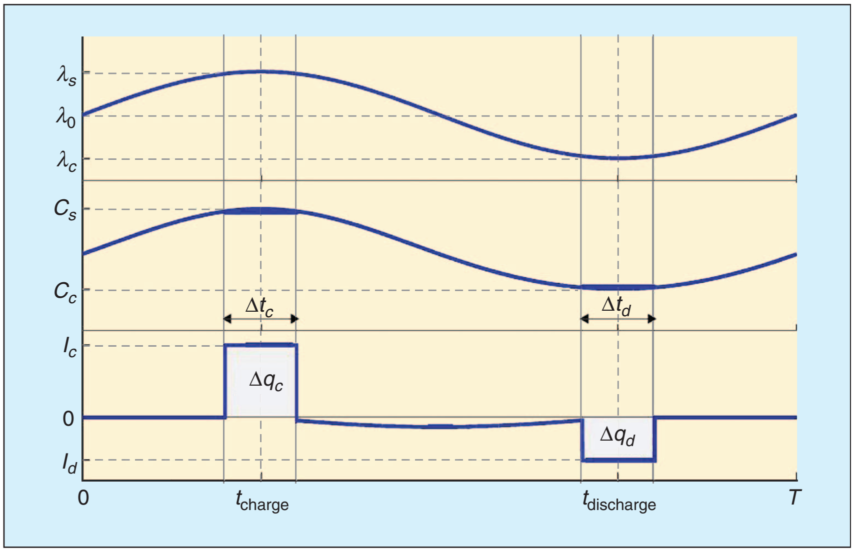

FIGURE 12 – The stretch ratio (λ), capacitance (C), and optimal current waveform as functions of time. The DE is stretched sinusoidally from ratio $\lambda_{\text{contracted}}$ to $\lambda_{\text{stretched}}$. The elastomer is charged with amplitude I_{charging}, while the discharging occurs with amplitude $I_{\text{discharging}}$.

Cost

Based on the tank experiments and real-sea demonstration, the price of electricity would be in the order of US$0.2/kWh. However, in the near future, the electric power generation per unit mass of EPAM material is expected to be twice as much as it is currently, which would lower the price to be closer to US$0.05–0.07/kWh [51], [55].

Current State

In August 2007, the first trial test of DE WEC (shown in Figure 11) in real sea conditions were carried out successfully at a location 1.6 km off the coast of St. Petersburg, Florida, in Tampa Bay. It demonstrated the principle idea of the device; it was able to generate electricity by utilizing ocean waves [53].

Conclusions

The potential in wave energy is noteworthy. This survey introduces the

TABLE 3–COMPARISON OF LIMPET (LIMP), PELAMIS (PEL), WAVE DRAGON (WD), AWS, AND EPAM BUOY (EAP).

	LIMP	PEL	WD	AWS	EAP
Operation principle	OWC	Attenuator	Overtopping terminator	Point absorber	Point absorber
Location	Onshore	Offshore floating	Offshore floating	Offshore submerged	Offshore floating
PTO	Wells turbine	Hydraulic	Hydroturbine	PMSL	EAP
Power conversion system		6 AEM	16 B2B	B2B	Various
Power quality	+	++	++	–	-
Cost of electricity (€/kWh)		0.07	0.11	0.03*	0.14
Development stage	++	++	+	0	-

*Price of the devices is not included.

current state of WEC technology and the major design problems and challenges that inventors and engineers face when building a WEC. It describes the major characteristics that can be used to categorize the devices. It highlights several WEC concepts, which are later described in detail and evaluated based on important properties (such as PTO and price of electricity). They are compared in Table 3. Based on the comparison, the Pelamis WEC is the leading candidate of WECs, although other technologies, such as Wave Dragon and EAP, have attractive opinions for the future.

Despite significant research and development, the concepts for converting the motion of the waves into electricity still do not show any signs of converging to any favored solution. The present technology is not able to present a reliable, functioning device that would be commercially used. Moreover, it is not clear which prototype will prevail and how a WEC needs to be chosen for specific locations. A significant problem arises regarding optimizing the WECs. All the subsystems need to be taken into account to reach an efficient operation and also the possible layout of the farm where the device will be deployed needs to be considered.

Acknowledgment

This work was supported in part by a Marie Curie Initial Training Network of the European Community's Seventh Framework Program under contract number PITN-GA-2008-215414, the Wavetrain2 program.

Biographies

Balazs Czech received his M.S. degree in mechanical engineering from the Budapest University of Technology and Economics, Hungary, in 2008. He is currently working toward his Ph.D. degree at the Delft University of Technology, The Netherlands. His research interests include wave energy, WECs, EAPs, and power electronics. He is a Student Member of the IEEE.

Pavol Bauer (P.Bauer@TUDelft.nl) received his master's degree in electrical engineering from the Technical University of Kosice in 1985, his Ph.D. degree from the Delft University of Technology in 1995, and the title of professor from the Brno University of Technology in 2008. Since 1990, he has been with Delft University of Technology, teaching power electronics and electrical drives. He has published more than 50 journals and 200 conference papers in his field, he is an author or coauthor of six books, and he holds an international patent. He organized several tutorials at international conferences. He is a Senior Member of the IEEE.

References

[1] European Thematic Network on Wave Energy, *Wave Energy Utilization in Europe. Current Status and Perspectives*, Greece: Centre for Renewable Energy Sources, 2002, pp. 1–32.

[2] J. Falnes, "A review of wave-energy extraction," *Marine Struct.*, vol. 20, no. 4, pp. 185–201, Oct. 2007. [Online]. Available: http://dx.doi.org/10.1016/j.marstruc.2007.09.001

[3] H. Polinder and M. Scuotto, "Wave energy converters and their impact on power systems," in *Proc. Int. Conf. Future Power Systems*, Nov. 18, 2005, pp. 9–18. [Online]. Available: http://dx.doi.org/10.1109/FPS.2005.204210

[4] J. F. Chozas and H. C. Soerensen, "State of the art of wave energy in Spain," in *Proc. IEEE Electrical Power and Energy Conf. (EPEC)*, Oct. 22–23, 2009, pp. 1–6.

[5] B. Drew, A. Plummer, and M. N. Sahinkaya, "A review of wave energy converter technology," *Proc. Inst. Mech. Eng., A: J. Power Energy*, vol. 223, no. 8, pp. 887–902, 2009.

[6] R. Bedard, G. Hagerman, M. Previsic, O. Siddiqui, R. Thresher, and B. Ram, "Final summary report—Project definition study, offshore wave power feasibility demonstration project," EPRI, USA, Rep. E2I EPRI Global WP 009—US Rev 2, Sept. 22, 2005.

[7] J. Cruz, *Ocean Wave Energy*. Berlin: Germany: Springer-Verlag, 2008.

[8] T. W. Thorpe, "The wave energy progamme in the UK and the European wave energy network," in *Proc. 4th Wave Energy Conf.*, 2000, pp. 19–27.

[9] F.G. Nielsen, M. Andersen, K. Argyriadis, S. Butterfield, N. Fonseca, T. Kuroiwa, M. Le Boulluec, S.-J. Liao, S. R. Turnock, and J. Waegter, "Ocean wind and wave energy utilization," in *Proc. 17th Int. Ship and Offshore Structures Congr.*, Southampton, U.K., Aug. 16–21, 2006, vol. 2, pp. 165–211.

[10] M. Previsic, "Wave power technologies," in *Proc. IEEE Power Engineering Society General Meeting*, June 12–16, 2005, vol. 2, pp. 2011–2016.

[11] T. W. Thorpe, "A brief review of wave energy," (A report produced for the UK Department of Trade and Industry, Oxfordshire, UK), Energy Technology Support Unit (ETSU), Rep. R120, 1999.

[12] A. Clément, P. McCullen, A. Falcão, A. Fiorentino, F. Gardner, K. Hammarlund, G. Lemonis, T. Lewis, K. Nielsen, S. Petroncini, Pontes, P. Schild, B.-O. Sjöström, H. C. Sørensen, and T. Thorpe, "Wave energy in Europe: Current status and perspectives," *Renewable Sustainable Energy Rev.*, vol. 6, no. 5, pp. 405–431, Oct. 2002. [Online]. Available: http://dx.doi.org/10.1016/S1364-0321(02)00009-6

[13] International Energy Agency and Ocean Energy System, "Status and research and development priorities, 2003," (A report produced for UK Department of Trade and Industry, UK), Waves and Marine Current Energy, DTI Rep. No. FES-R-132, 2002.

[14] "AEA Energy and Environment on the Behalf of Sustainable Energy Ireland for the IEA's Implementing Agreement on Ocean Energy Systems," "Review and analysis of ocean energy systems development and supporting policies," IEA, Ireland, June 28, 2006. [Online]. Available: http://www.ieaoceans.org/_fich/6/Review_Policies_on_OES_2.pdf

[15] N. T. Meyer and K. Nielsen, "The Danish wave energy program second year status," in *Proc. 4th European Conf. Wave Energy*, Denmark, 2000, pp. 10–18.
[16] M. Rugbjerg, K. Neilsen, J. H. Christiansen, and V. Jacobsen, "Wave energy in the Danish part of the North Sea," in *Proc. 4th European Wave Energy Conf.*, Aalborg Univ., Denmark, Dec. 4–6, 2000.
[17] Rambøll, 'DHI Water and environment and the Danish Meteorological Institute for the Danish Energy Agency,' "Kortloegning af bølgeenergiforhold i den danske del af Nordsøen," J. no. 51191/97-0014, 1999, Denmark. [Online]. Available: http://www.waveenergy.dk/files/rep50105.pdf
[18] ESBI-ETSU, Total renewable energy resource in Ireland, ESBI, Dublin, Ireland, EU ALTENER contract XVII/4.1030/T4/95/IRL, Rep. No. PA598-R2-001, 1997.
[19] D. Mollison, "Ireland's wave power resource," National Board for Science and Technology, Dublin, Ireland, Rep. No. PB-84-109016, 1992.
[20] Marine Institute Sustainable Energy Ireland, "Options for the development of wave energy in Ireland," Public Consultation Report, Nov. 2002. [Online]. Available: http://www.seai.ie/Archive1/Files_Misc/wave.pdf
[21] D. Mollison and M. T. Pontes, "Assessing the Portuguese wave-power resource," *Energy*, vol. 17, no. 3, pp. 225–268, Mar. 1992. [Online]. Available: http://dx.doi.org/10.1016/0360-5442(92)90053-3
[22] R. E. Harris, L. Johanning, and J. Wolfram, "Mooring systems for wave energy converters: A review of design issues and choices," in *Proc. 3rd Int. Conf. Marine Renewable Energy*. Blyth,: United Kingdom, 2004, pp. 1–10. [Online]. Available: http://www.oreg.ca/web_documents/mooringsystems.pdf
[23] L. M. C. Gato and F. Falcao, "On the theory of the Wells turbine," *J. Eng. Gas Turbine Power*, vol. 106, no. 3, pp. 628–633, 1984.
[24] A. Brito-Melo, L. M. C. Gato, and A. Sarmento, "Analysis of Wells turbine design parameters by numerical simulation of the OWC performance," *Ocean Eng.*, vol. 29, no. 12, p. 146, 2002.
[25] T. Setoguchi and M. Takao, "Current status of self rectifying air turbines for wave energy conversion," *Energy Convers. Manage.*, vol. 47, no. 15–16, pp. 2382–2396, 2006.
[26] T. Setoguchi, S. Santhakumar, H. Maeda, M. Takao, and K. Kaneko, "A review of impulse turbine for wave energy conversion," *Renewable Energy*, vol. 23, no. 2, pp. 261–292, June 2001. [Online]. Available: http://dx.doi.org/10.1016/S0960-1481(00)00175-0.
[27] A. Thakker, P. Frawley, H. B. Khaleeq, Y. Abugihalia, and T. Setoguchi, "Experiment and CFD analysis 0.6 m impulse turbine with fixed guide vanes," in *Proc. 11th Int. Offshore and Polar Engineering Conf. (ISOPE)*, 2001, pp. 625–629.
[28] R. Henderson, "Design, simulation, and testing of a novel hydraulic power takeoff system for the Pelamis wave energy converter," *Renewable Energy*, vol. 31, no. 2, pp. 271–283, Feb 2006. [Online]. Available: http://dx.doi.org/10.1016/j.renene.2005.08.021.
[29] M. A. Mueller, "Electrical generators for direct drive wave energy converters," *IEE Proc. Gener. Transm. Distrib.*, vol. 149, no. 4, pp. 446–456, July 2002.
[30] H. Polinder, B. C. Mecrow, A. G. Jack, P. Dickinson, and M. A. Mueller, "Linear generators for direct-drive wave energy conversion," in *Proc. Electric Machines and Drives Conf.*, June 2003, vol. 2, pp. 798–804.
[31] H. Polinder, M. E. C. Damen, and F. Gardner, "Linear PM generator system for wave energy conversion in the AWS," *IEEE Trans. Energy Conversion*, vol. 19, no. 3, pp. 583–589, 2004.
[32] http://www.emec.org.uk/wave_energy_developers.asp
[33] T. Heath, T. Whittaker, and C. Boake, "Research into the further development of the limpet shoreline wave energy plant," DTI Sustainable Energy Programmes, Boulder, CO, ETSU V/06/00183/REP, 2002.
[34] Wavenet, EU Consortia, "Results from the work of European thematic network on wave energy," Rep., 2003. [Online]. Available: http://www.offshorecenter.dk/log/bibliotek/WaveNet%20Full%20Report%2811.1%29.pdf
[35] http://www.voith.com/press/560617.htm
[36] A. L. Rodrigues and A. S. Garção, "Pelamis converter for wave energy extraction," in *Proc. 5th Portuguese-Mozambique Conf. Engineering*, 2008, pp. 1–12.
[37] R. Yemm, R. Henderson, and C. Taylor, "The OPD pelamis WEC: Current status and onward programme," in *Proc. 4th European Wave Energy Conf.*, Aalborg, Denmark, 2000, pp. 104–109.
[38] O. Siddiqui and R. Bedard, "Feasibility assessment of offshore wave and tidal current power production: A collaborative public/private partnership," in *Proc. IEEE Power Engineering Society General Meeting*, June 12–16, 2005, vol. 2, pp. 2004–2010.
[39] http://www.pelamiswave.com/our-projects/project-overview
[40] H. C. Soerensen, R. Hansen, E. Friis-Madsen, W. Panhauser, G. Mackie, H. H. Hansen, P. Frigaard, T. Hald, W. Knapp, E. Holmen, B. Holmes, G. Thomas, and P. Rasmussen, "The Wave Dragon—Now ready for test in real sea," in *Proc. 4th European Wave Energy Conf.*, Denmark, Aalborg, Dec. 4–8, 2000.
[41] J. P. Kofoed, P. Frigaard, E. Friis-Madsen, and H. C. Sørensen, "Prototype testing of the wave energy converter Wave Dragon," *Renew. Energy*, vol. 31. pp. 181–189, 2006.
[42] P. Frigaard, J. P. Kofoed, E. Friis-Madsen, and H. C. P. Sørensen, "Wave dragon. Wave power plant using low-head turbines," in *Proc. Hidroenergia '04*, Falkenberg, Sweden, 2004, pp. 1–8.
[43] E. Friis-Madsen, L. Christensen, J. P. Kofoed, and J. Tedd, "World's largest wave energy project 2007 in Wales," in *Proc. Powergen Europe Conf.*, 2006, pp. 1–16.
[44] L. Christensen, E. Friis-Madsen, and J. P. Kofoed, "The wave energy challenge—The Wave Dragon case," in *Proc. PowerGen Europe Conf.*, 2005, pp. 1–20.
[45] http://www.wavedragon.net/
[46] G. Spagnuolo, G. Petrone, S. V. Araujo, C. Cecati, E. Friis-Madsen, E. Gubia, D. Hissel, M. Jasinski, W. Knapp, M. Liserre, P. Rodriguez, R. Teodorescu, and P. Zacharias, "Renewable energy operation and conversion schemes: A summary of discussions during the seminar on renewable energy systems," *IEEE Ind. Electron. Mag.*, vol. 4, no. 1, pp. 38–51, Mar. 2010.
[47] M. Jasinski, M. Malinowski, M. P. Kazmierkowski, H. C. Soerensen, E. Friis-Madsen, and D. Swierczynski, "Control of AC/DC/AC Converter for multi MW wave dragon offshore energy conversion system," in *Proc. IEEE Int. Symp. Industrial Electronics, ISIE*, June 4–7, 2007, pp. 2685–2690.
[48] K. Rothenhagen, M. Jasinski, and M. P. Kazmierkowski, "Grid connection of multi-megawatt clean wave energy power plant under weak grid condition," in *Proc. 13th Power Electronics and Motion Control Conf. (EPE-PEMC '08)*, Sept. 1–3, 2008, pp. 1904–1910.
[49] M. G. Souza de Prado, F. Gardner, M. E. C. Damen, and H. Polinder, "Modelling and test results of the Archimedes wave swing," *Proc. Inst. Mech. Eng., A: J. Power Energy*, vol. 220, no. 8, pp. 855–868, 2006.
[50] B. Czech, P. Bauer, H. Polinder, Y. Zhou, and P. Korondi, "Comparing the electrical transmission systems for Archimedes Wave Swing parks," in *Proc. 8th European Wave and Tidal Energy Conf. (EWTEC '09)*, Uppsala, Sweden, Sept. 7–10, 2009, pp. 36–43.
[51] S. Chiba, H. Prahlad, R. Pelrine, and R. Kornbluh, "Innovative power generators using EPAM," *Proc. 15th Japan Institute of Energy Conf.* Tokyo: Japan: Kogakuin Univ., Aug. 3–4, 2006, pp. 297–298.
[52] R. van Kessel, B. Czech, P. Bauer, and J. A. Ferreira, "Optimizing the dielectric elastomer energy harvesting cycles," in *Proc. 36th Annu. Conf. IEEE Industrial Electronics Society (IECON '10)*, Nov. 7–10, 2010, pp. 1281–1286.
[53] S. Chiba, M. Waki, R. Kornbluh, and R. Pelrine, "Innovative wave power generation system using electroactive polymer artificial muscles," in *Proc. OCEANS 2009—EUROPE*, May 11–14, 2009, pp. 1–3.
[54] E. Pelrine, R. Kornbluh, J. Eckerle, and H. Prahlad, "Circuit for electroactive polymer generators," Patent WO/2008/112583, Sept. 18, 2008.
[55] S. Chiba, M. Waki, K. Masuda, and T. Ikoma, "Current status and future prospects of electric generators using electroactive polymer artificial muscle," in *Proc. 2010 IEEE OCEANS*, Sydney, May 24–27, 2010, pp. 1–5.
[56] H. C. Lo, T. Mckay, B. M. O'Brien, I. Anderson, and E. Calius, "Circuit design considerations for regulating energy generated by dielectric elastomer generators," in *Proc. Electroactive Polymer Actuators and Devices (EAPAD) 2011, SPIE 7976, 79760C*, 2011, pp. 1–8.
[57] H. Ibrahima, A. Ilincaa, and J. Perronb, "Energy storage systems—Characteristics and comparisons," *Renewable Sustainable Energy Rev.*, vol. 12, no. 5, pp. 1221–1250, June 2008.
[58] J. M. Carrasco, L. G. Franquelo, J. T. Bialasiewicz, E. Galvan, R. C. P. Guisado, Ma. A. M. Prats, J. I. Leon, and N. Moreno-Alfonso, "Power-electronic systems for the grid integration of renewable energy sources: A survey," *IEEE Trans. Ind. Electron.*, vol. 53, no. 4, pp. 1002–1016, June 2006.
[59] K. Thorburn, H. Bernhoff, and M. Leijon, "Wave energy transmission system concepts for linear generator arrays," *Ocean Eng.*, vol. 31, pp. 1339–1349, 2004.
[60] R. Philipp, T. S. Johanning, and G. H. Smith, "Towards component reliability testing for marine energy converters," *Ocean Eng.*, vol. 38, no. 2–3, pp. 360–370, Feb. 2011.
[61] P. R. Thies, J. Flinn, and G. H. Smith, "Is it a showstopper? Reliability assessment and criticality analysis for wave energy converters" in *Proc. 8th European Wave and Tidal Energy Conf. (EW TEC '09)*, Uppsala, Sweden, Sept. 7–10, 2009, pp. 21–30.
[62] A. F. de and O. Falcão, "Wave energy utilization: A review of the technologies," *Renew. Sustain. Energy Rev.*, vol. 14, no. 3, pp. 899–918, Apr. 2010.