Ocean Wave Energy Conversion

Submitted To

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ABSTRACT

Ocean energy conversion has been of interest for many years. Recent developments such as concern over global warming have renewed interest in the topic. This report focuses on wave energy converters (WEC) as opposed to ocean current energy converters. The point absorber and oscillating water column WEC devices are addressed with regards to commercial prospects, environmental concerns, and current state-of-the art. This report also provides an overview of the energy found in ocean waves and how each type of device utilizes the available ocean wave energy.

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1.0 INTRODUCTION

The ocean holds a tremendous amount of untapped energy. Although the oil crisis of the 1970s increased interest in ocean energy, relatively few people have heard of it as a viable energy alternative. In fact, hydroelectric dams are the only well known, mass producing water-based energy, but the ocean is also a highly exploitable water-based energy source. This report provides an overview of the energy found in ocean waves, the current state-of-the art in methods used to extract this energy, commercial prospects, and environmental concerns associated with ocean wave energy extraction.

2.0 OCEAN ENERGY RESOURCES

Ocean energy comes in a variety of forms such as marine currents, tidal currents, geothermal vents, and waves. All are concentrated forms of solar or gravitational energy to some extent. Moreover, wave energy provides "15-20 times more available energy per square metre than either wind or solar" [16]. The most commercially viable resources studied so far are ocean currents and waves.

Some research has been conducted on constructing a heat cycle based on geothermal vents, but this work has led to the conclusion that geothermal vents are not commercially viable [11]. On the other hand, ocean current and wave energy has already undergone limited commercial development and is therefore of more interest.

2.1 OCEAN CURRENTS

Two main types of ocean currents exist: marine currents and tidal currents. Both types are influenced by the rotation of the Earth and are highly predictable. Marine currents such as the Gulf Stream in the Atlantic originate from differences in water temperature within the ocean. When water at the Equator warms up, it moves towards the poles then cools, sinks, and flows back towards the Equator. The speed with which this water conveyor belt moves is cyclic in that it speeds up and slows down over about a ten year period [21].

Tidal currents occur in a very different manner than marine currents. The tides transpire as a result of the Moon's gravitational pull on the ocean. Depending on location and geography, tidal currents come in half-day (semi-diurnal), daily (diurnal), and 14-day cycles [9]. Instead of a constant flow in one direction as with marine currents, tidal currents flow in one direction at the beginning of the cycle and reverse directions at the end of the cycle.

Estimates conclude that marine and tidal currents combined contain about 5 TW [9] of energy, which is on the scale of the world's total power consumption. Prototypes of marine current generators have been deployed in both Europe and the US. The technology used to harbor this type of energy is similar to hydroelectric, and some models may even be described as looking like underwater wind turbines.

2.2 OCEAN WAVES

Ocean waves arise from the transfer of energy from the sun to wind then water. Solar energy creates wind which then blows over the ocean, converting wind energy to wave energy. Once converted, this wave energy can travel thousands of miles with little energy loss. Most importantly, waves are a regular source of power with an intensity that can be accurately predicted several days before their arrival [20]. Furthermore, wave energy is more predictable than wind or solar energy. Fig. 1 depicts wave power levels in kW/m of wave crest, the typical units for measuring wave energy.

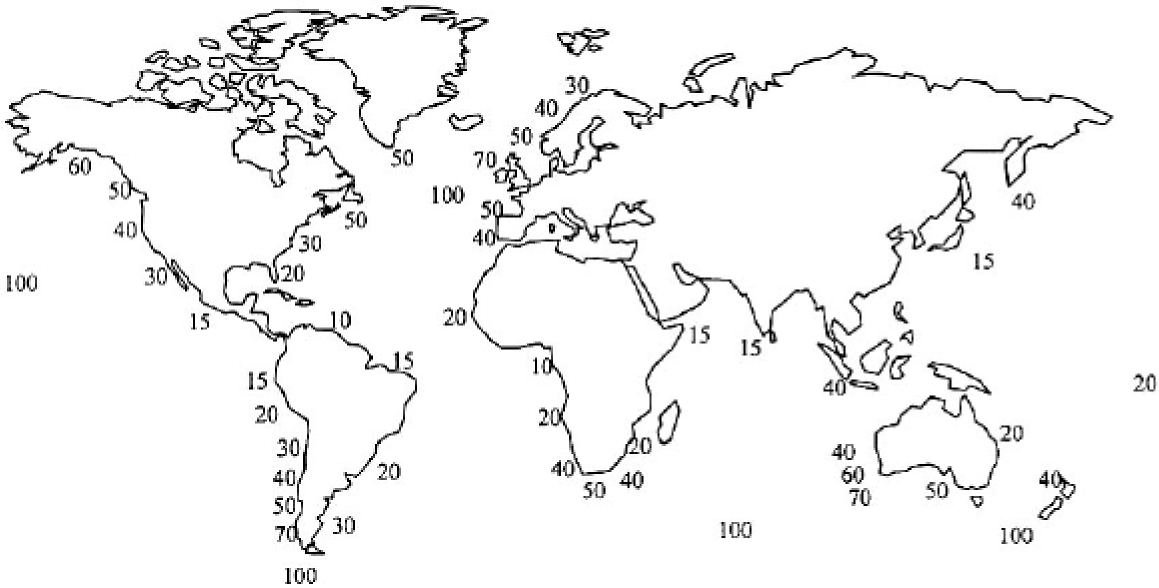

Fig. 1 Approximate global distribution of wave power levels (kW/m of wave front)
T. W. Thorpe, ETSU, November 1999 [11]

There is approximately 8,000 – 80,000 TWh/yr or 1 – 10 TW of wave energy in the entire ocean [9], and on average, each wave crest transmits 10 – 50 kW per meter. The energy levels depicted in Fig. 1 are important to keep in mind when designing any sort of wave power take-off device, but it should also be noted that wave power decreases closer to the shore because of frictional losses with the coastline.

2.3 WAVE CLIMATE

In order to assess an area for wave energy development, the wave climate must be defined. The wave climate describes an area's wave height distribution, wave length distribution, and total mean water depth. From these parameters, one can compute wave power levels. A significant piece of data to gather from Fig. 1 is that the waves present on the western edge of the continents contain more energy because of the west-to-east winds. An important fact not shown in Fig. 1 is that average wave power is cyclical with winter bringing energy levels up to six times greater than summer [13].

3.0 WAVE ENERGY CALCULATIONS

> "The utilization factor for wave power – the ratio of yearly energy production to the installed power of the equipment – is typically 2 times higher than that of wind power. That is whereas for example a wind power plant only delivers energy corresponding to full power during 25% of the time (i.e. 2,190 h out of the 8,760 h per year) a wave power plant is expected to deliver 50% (4,380 h/year)." [14]

While we know that wave power is more energy dense than wind power and produces power for a larger percentage of the year, we still do not know how to calculate the power available from a wave. This is important for the design process of a wave energy converter. First, the power and forces acting on the device should be assessed, then the device may be sized for the desired energy output. The next sections explain how to calculate the wave energy and power and how to size point absorbers and oscillating water columns for a given power level. More information on these wave energy converters can be found in section 5.

3.1 WAVE ENERGY AND POWER

The following analysis describes a wave's energy and power characteristics. Table 1 complements Fig. 2's depiction of the variables used in Section 3's wave energy analysis with units.

Table 1. Wave Nomenclature as used in Fig. 2 and Section 3

Variables	
SWL	mean seawater level (surface)
$E_{density}$	wave energy density [J/m^2]
$E_{wavefront}$	energy per meter wave front [J/m]
$P_{density}$	wave power density [W/m^2]
$P_{wavefront}$	power per meter wave front [W/m]
h	depth below SWL [m]
ω	wave frequency [rad/sec]
λ (or L)	wavelength [m] = $gT^2/(2\pi)$
ρ_{water}	seawater density [1000 kg/m^3]

g	gravitational constant [9.81 m/s^2]
A	wave amplitude [m]
H	wave height [m]
T	wave period [s]
C	celerity (wave front velocity) [m/s]

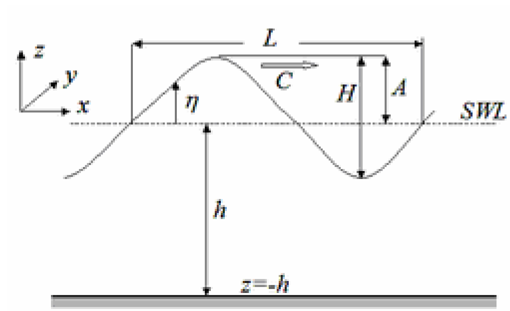

Fig. 2 Wave Nomenclature [19]

3.1.1 Energy and Power Density

The energy density of a wave, shown in equation 1, is the mean energy flux crossing a vertical plane parallel to a wave's crest. The energy per wave period is the wave's power density. Equation 2 shows how this can be found by dividing the energy density by the wave period [18, 19]. Fig. 3 illustrates how wave period and amplitude affect the power density.

$$E_{density} = \rho_{water} g H^2/8 = \rho_{water} g A^2/2 \qquad (1)$$

$$P_{density} = E_{density}/T = \rho_{water} g H^2/(8T) = \rho_{water} g A^2/(2T) \qquad (2)$$

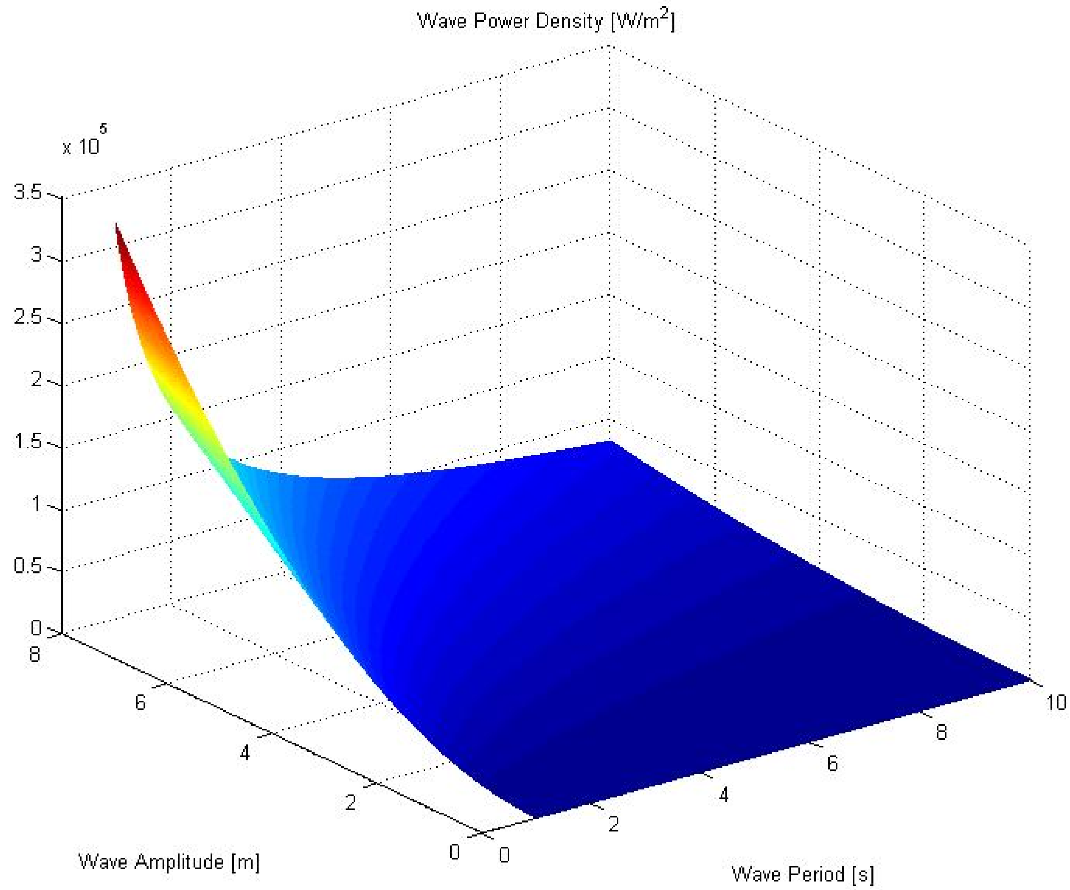

Fig. 3 Wave Power Density

3.1.2 Power Per Meter of Wave Front

A wave resource is typically described in terms of power per meter of wave front (or wave crest). This can be calculated by multiplying the energy density by the wave celerity (wave front velocity) as equation 3 demonstrates [19]. Fig. 4 characterizes an increase in the amplitude and period of a wave increases the power per meter of wave front.

$$P_{wavefront} = C{*}E_{density} = \rho_{water} g^2 H^2/(16\omega) = \rho_{water} g^2 A^2/(4\omega) \qquad (3)$$

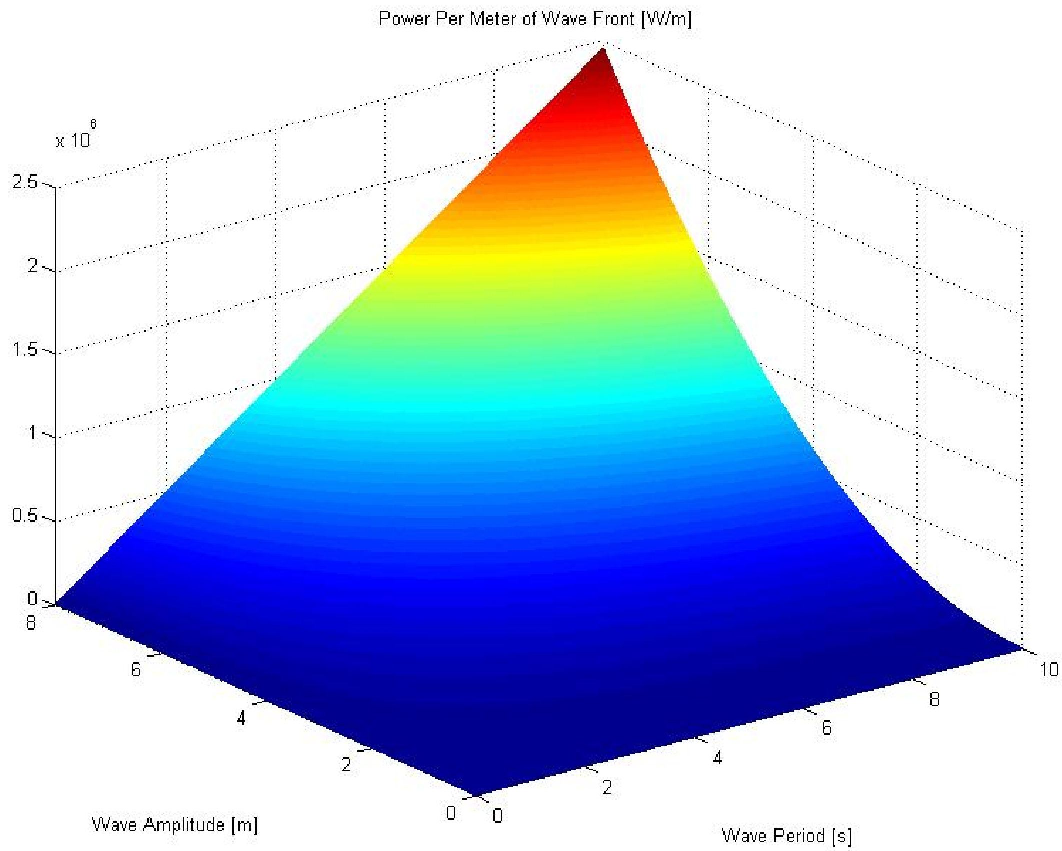

Fig. 4 Power Per Meter of Wave Front

3.1.3 Energy at Varying Depths

To properly size an underwater wave energy converter, the wave power at the operating depth must be known. In general, the wave power below sea level decays exponentially by $-2\pi d/\lambda$ where d is the depth below sea level. This property is valid for waves in water with depths greater than $\lambda/2$. Equation 4 gives the relationship between depth and surface energy [1].

$$E(d) = E(d{=}SWL) * e^{-2\pi d/\lambda} \tag{4}$$

3.2 ENERGY CONVERSION IN POINT ABSORBER

The equations governing the float and tube type point absorber presented below are different yet work on the same principle. As previously mentioned, more information on these wave energy converters is presented in section 5.

3.2.1 Float Type

The float on this point absorber bobs up and down with the change in mass above it. As a wave crest approaches, the water mass increases above the float, thus pushing it down. The forces acting on the float may be modeled via Newton's equation, F=ma, which is shown in equation 5. The mass of water is taken to be $\rho_{water}HA_{float}$, and gravity is the accelerating force. To calculate the power transferred to the float in equation 6, F_{water} is multiplied by the velocity of the float, where the velocity is the stroke length divided by half the wave period. These equations may be used for sizing the float and reactionary forces required in the generator.

$$F_{water} = (\rho_{water}HA_{float})g \quad (5)$$

$$P_{generated} = F_{water}(2L_{stroke}/T) \quad (6)$$

Where:

F_{water} ≡ force of water mass on the float [N]

A_{float} ≡ area of float [m^2]

$P_{generated}$ ≡ generated system power [W]

L_{stroke} ≡ length of float stroke [m]

3.2.2 Tube Type

The tube type point absorber equations can be more complicated than the float type if calculated using Bernoulli's theory for unsteady flow. An easier method of evaluating the power for the tube type point absorber is found by calculating the force on the piston within the tube based on how much power is to be developed and how long the piston stroke is. By dividing the generated force from equation 7 by the pressure difference across the tube, the area of the piston may be determined in equation 8.

$$F_{generated} = P_{desired}T/(2L_{stroke}) \quad (7)$$

$$A_{piston} = F_{generated}/p_{diff} \quad (8)$$

Where:

$F_{generated}$ ≡ force of water pressure on the piston [N]

$P_{desired}$ ≡ desired system power [W]

L_{stroke} ≡ length of piston stroke [m]

A_{piston} ≡ area of piston [m^2]

p_{diff} ≡ pressure difference across tube [Pa = N/m^2]

3.3 ENERGY CONVERSION IN AN OSCILLATING WATER COLUMN

The oscillating water column (OWC) energy equations are similar to those used for wind turbines. Equation 9 [18] expresses the power available from the airflow in the OWC's chamber. The air flow kinetic energy term, $v_{air}^3 A_{duct} \rho_{air}/2$, is common to wind turbine analysis but the air pressure term, $p_{air} v_{air} A_{duct}$, is unique to this application. From equation 9, it can be seen that the size of the duct and the air flow through the duct play a significant role in an OWC.

$$P_{OWC} = (p_{air} + \rho_{air} v_{air}^2/2)\, v_{air} A_{duct} \qquad (9)$$

Where:

P_{OWC} ≡ power available to turbine in OWC duct [W]

v_{air} ≡ airflow speed at the turbine [m/s]

A_{duct} ≡ area of turbine duct [m^2]

p_{air} ≡ pressure at the turbine duct [Pa = N/m^2]

ρ_{air} ≡ air density [kg/m^3]

4.0 OCEAN WAVE ENERGY COMMERCIALIZATION

> "The footprint of a 100MW conventional power plant superstructure, including surrounding grounds, fuel unloading areas, waste settling ponds, and additional facilities can require up to 2 square miles of valuable real estate. A comparable OPT power plant would occupy less than 1 square mile of unused ocean surface out of sight from the shore." [17]

The above quote along with the fact that over 30 percent of the human population lives within 60 miles of the coastline [15] explains why wave energy has entered the commercial market. Commercialization of wave energy converters has mostly occurred in the U.S. with several installations planned along the coasts. Europe still regards this technology to be in the research stage even though at least two designs have been incorporated by European utilities for prototyping purposes. China, India, and Japan are also involved in wave energy; however their involvement is mostly institutional and focused on oscillating water column devices. The U.S. has seen an explosion of growth in the number of companies offering wave energy devices with 25 or more at the end of 2005. Europe has almost as many companies with the majority residing in the U.K. Both American and European companies depend heavily on government subsidies to continue operations until prototypes are ready for major installations. Appendix A offers an overview of companies around the world involved in ocean energy but does not claim to be complete.

5.0 FUNDAMENTAL WAVE ENERGY CONVERTER (WEC) CLASSIFICATIONS

Patents relating to wave energy extraction date back to the 1920s in the U.S. and even further elsewhere. Those devices are predecessors of the modern-day oscillating water column (OWC) as well as the float-type point absorber. Unlike the goal of today's wave energy converters, the first devices were meant to compress air or pump water. Recent technological improvements have enabled engineers to use the compressed air in an OWC device to drive a turbine and the water pumped by a point absorber to run a generator. Table 2 breaks down the different ocean energy conversion devices into two main categories.

Table 2. Ocean Energy Converter Classifications

Ocean Flow Energy Converter		**Ocean Wave Energy Converter**	
Tidal Flow	*Ocean Currents*	*Turbine -type*	*Buoy-type*
Tidal Lagoon Tidal Dam	Bi-Directional Turbine Uni-Directional Turbine	Oscillating Water Column (OWC) Overtopping Wave Energy Converter	Tube type Float type

This report does not intend to focus on ocean current energy converters because their technology is already mature compared to wave energy conversion. Additionally, the negative environmental impact of ocean current converters is likely to be greater than wave energy converters. The main reasons for this impact are that current converters have more moving parts that may injure sea life and some converters require currents to be funneled into turbines thereby blocking sections of water flow. One may relate this situation to hydroelectric dams in that the natural sedimentation process is disrupted with unnatural barriers that also block migration paths for some species.

As seen from Table 2 there are two fundamental types of Wave Energy Converters (WEC), although some authors have broken down these types into even more classifications based on their orientation and functionality. The first type of WEC to get attention from the research community is the turbine-type while buoy-type converters are a newer idea. Both have operational prototypes, some of which have even been commercialized.

5.1 TURBINE TYPE

The turbine-type wave energy converter employs a turbine as an energy conversion device. These come in many different forms, the most prominent being the oscillating water column. The other type of device is described as an overtopping WEC.

5.1.1 Oscillating Water Column (OWC) Wave Energy Converter

The oscillating water column (OWC) as illustrated in Fig. 5 operates much like a wind turbine via the principle of wave induced air pressurization. Some sort of closed containment housing (air chamber) is placed above the water and the passage of waves changes the water level within the housing. If the housing is completely sealed, the rising and falling water level will increase and decrease the air pressure respectively within the housing. With this concept in mind, we can place a turbine on top of the housing through which air may pass into and out of. Air will flow into the housing during a wave trough and will flow out of the housing during a wave crest. Because of this bidirectional air flow, the turbine must be designed to rotate in only one direction no matter the direction of air flow. The Wells Turbine was designed for this type of application and is used in most OWC devices today; however, Energetec is working on a new bidirectional turbine for their OWCs [9].

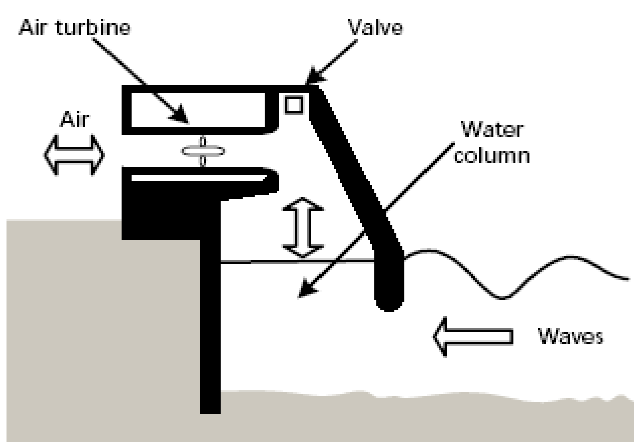

Fig. 5 Oscillating Water Column Device [9]

5.1.1.1 OWC Design

The air chamber within the OWC housing must be designed with the wave period, significant wave height, and wave length characteristics of the local ocean climate in mind. If the housing is not sized correctly, waves could resonate within the air chamber. This resonating effect causes a net zero passage of air through the turbine. Ideally, the air chamber dimensions will be designed to maximize energy capture in the local wave climate while research has shown that the generator design (generator size and generator coefficient) is almost completely independent of wave climate such that only areas of extreme wave energy benefit from larger generators and only marginally so [2].

In addition to sizing the air chamber with respect to the wave climate, the air chamber must also be conducive to air flow through the turbine. This is best achieved with a funnel shaped design such that the chamber narrows from the water surface level to the turbine. This will concentrate the air flow through the turbine.

5.1.1.2 OWC Placement: Near Shore vs. Shoreline

OWC devices are placed on the shoreline or near the shore. The shoreline devices are placed where the waves break on the beach and are known to be noisy. The near shore devices are fixedly moored to the ocean bottom in that same manner as offshore wind turbines or slack moored so as to respond to changes in mean water level, i.e. tides. The housing is placed just above the water surface.

Both near shore and shoreline placements have their pros and cons. Of foremost concern is that the wave energy is greater offshore than at the shoreline, so more energy is available for capture in a near shore OWC. Wave energy concentration near shore through natural phenomena such as refraction or reflection can compensate for some or all of this energy dissipation, but there are few areas where this occurs. The con to being offshore is that installation and maintenance costs increase. Both the near shore and shoreline OWCs are eye sores since they are visible over the ocean surface, hence both will experience public resistance to their installation. Then again, the shoreline device will interfere with beachgoers more directly and will therefore be met with the most public resistance. With the need for public acceptance and decent available energy, one may conclude that the near shore OWC is the better device.

The changing mean ocean surface level accompanying tides may pose problems for a fixedly moored OWC. Nonetheless, a fixedly moored device maintains its position better than a slack moored device so as to provide more resistance to incoming waves and therefore produce more energy. Another tradeoff between the fixedly and slack moored OWC is that while the fixedly moored OWC collects more energy, the slack moored OWC provides some flexibility in rough seas which might damage a fixedly moored device. Also, the installation costs of a slack moored device are less than a fixedly moored device because a rigid foundation does not need to be constructed.

5.1.2 Overtopping Wave Energy Converter

The overtopping wave energy converter works in much the same way a hydroelectric dam works. Waves roll into a collector which funnels the water into a hydro turbine as depicted in Fig. 6. The turbines are coupled to generators which produce electricity. After the waves flow through the turbines, they continue through the ocean. A mesh grid functions to extract trash and marine debris before the waves pour into the turbine. The overtopping WEC can be placed on the shoreline or near shore but are more commonly placed at a near shore location. As with the OWC, the overtopping WEC may be slack moored or fixedly moored to the ocean bottom, and the issues associated with these mooring options are the same as with the OWC. It should be noted that overtopping wave energy converters are not as common as OWCs.

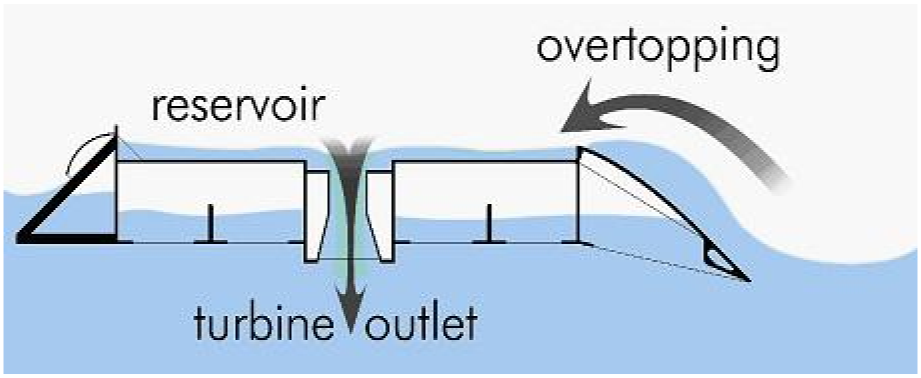

Fig. 6 Overtopping WEC [22]

5.2 BUOY TYPE

The buoy type wave energy converter is also known as a "point absorber" because it harvests energy from all directions at one point in the ocean. These devices are placed at or near the ocean surface away from the shoreline. They may occupy a variety of ocean depths ranging from shallow to very deep water depending on the WEC design and the type of mooring used. There are several types of point absorbers with the most common being the hollow tube type and the float type, although there are other forms.

5.2.1 Tube Type

This type of WEC consists of a vertically submerged, neutrally buoyant (relative to its position just below the mean ocean surface level) hollow tube. The tube allows water to pass through it, driving either a piston or a hydro turbine. The piston power take-off method is better suited for this application because the rate of water flowing through the tube is not rapid [1]. There are two tube arrangements such that one end may be closed and the other open or both open. With both ends closed, no water flows and the device becomes the float type.

The hollow tube type WEC works on the concept that waves cause pressure variations at the surface of the ocean. The long, cylindrical tube experiences a pressure difference between its top and bottom, causing water to flow into and out of the open end(s) of the tube. When a wave crest passes above a tube, water will flow down the tube, and when a wave trough passes above the tube, water will flow up the tube. This flow will push a piston which may either power a drive belt, a hydraulic system, or a linear generator.

In the case of the drive belt, the piston is connected to a belt which turns at least one gear. The gear may be connected to a gear box to increase the speed of rotation of the shaft which turns the rotor of an electric generator. With a hydraulic system, the piston pumps hydraulic fluid through a hydraulic motor which is coupled to an electric generator. The hydraulic system is preferred over the drive belt due to maintenance issues [1]. Also, multiple WECs may be connected to one electric generator through a hydraulic system. When the piston is connected to a linear generator, it bypasses the hydraulics process and the gear box of a drive belt. Power take-off with this method is a result of the up and down movement of the linear generator's translator (in the case of linear generators, the rotor is referred to as a translator), which is directly coupled to the piston.

5.2.2 Float Type

As mentioned above, the float-type WEC is some sort of sealed tube or other type of cavity. It will most likely be filled with air or water or a mix of the two. In order to make the sealed cavity positively buoyant so that it floats on top of the ocean surface, it should contain some air. If the cavity is to be just below the surface, it should contain water at the pressure of the depth it is placed thus making it neutrally buoyant with respect to its depth. The behavior of the float may be altered by varying the pressure within the cavity.

The float type WEC in Fig. 7 operates with several different power take-off methods. The floater will move in different directions relative to wave motion depending on its location above or below the water. If the floater is on the surface, it will move up and down with the wave. This poses control problems because the wave height may exceed the WEC's stroke length (how far up and down the floater is permitted to move by design). The worst possible outcome could be damage to the WEC during a storm when wave heights are extreme. The solution to this problem of limited stroke length is to place the tube under water as described above.

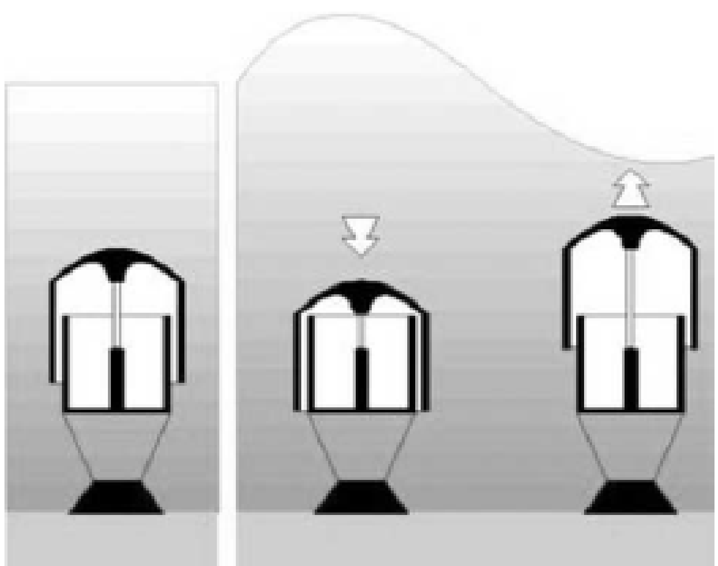

Fig. 7 Below Surface Point Absorber [4]

Fig. 7 illustrates the motion of a below surface point absorber relative to wave motion. When a wave crest passes overhead, the extra water mass pushes the float down, and when a wave trough passes, the absence of water mass pulls the float up since it becomes lighter than the water overhead. A control system can pump water and/or air into the float to vary buoyancy and thus restrain the float if large wave heights are experienced. Moreover, if a rough storm occurs, the entire system will be underwater and out of harm's way.

As with the tube type point absorber, the up and down motion of the floater relative to some stationary foundation will act on a piston. This piston can be connected to a generator using any of the methods described earlier. With a float instead of a tube, other conversion mechanisms may be utilized.

Rather than a piston, the float may act on what is called a "hose pump" as seen in the Fig. 8. It is similar to a hydraulic system in that the hose pressurizes seawater which drives a generator. The difference with the hose pump system is the method of pressurization. A long flexible hose is attached to a float and a stationary reaction plate. The float moves relative to the reaction plate, stretching and constricting the hose. When the hose is stretched, it pulls in seawater, and when the hose is constricted, pressurized water is pushed out to a generator.

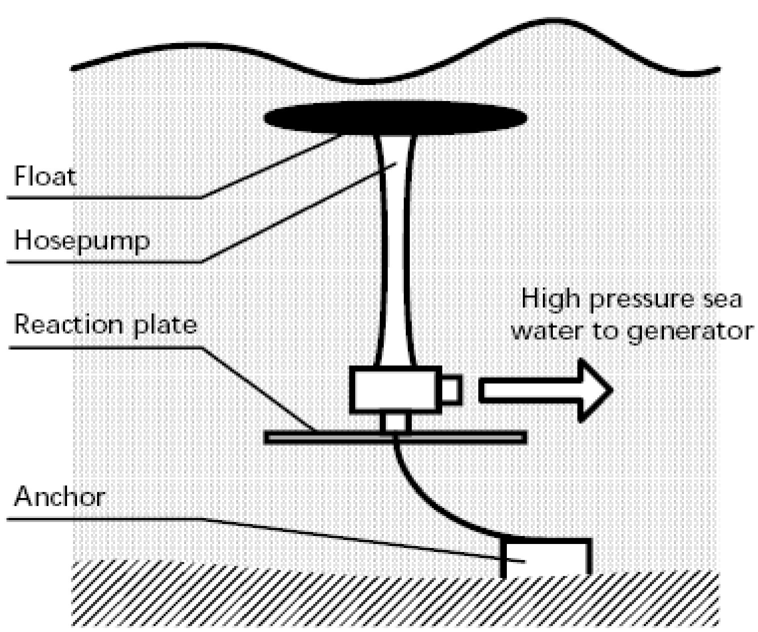

Fig. 8 Hose Pump [9]

5.3 OTHER FORMS WORTHY OF NOTICE

The Pelamis is unique among wave energy converters. Although it also employs the use of a hydraulic system, it is not driven by the up and down motion of a float. The Pelamis, with its linked chain of cylindrical sections, looks like a snake floating on the ocean surface. The cylindrical sections are held together by hinged joints whose heave and sway motion pumps high pressure hydraulic oil. The mooring system allows the Pelamis to retain its position but is flexible enough to swing head-on into oncoming waves [25].

Fig. 9 The Pelamis WEC [25]

5.4 IMPORTANT DESIGN PARAMETERS

There are numerous factors that affect the design of both the OWC and point absorber type of wave energy converters. Table 3 lists some of the most useful design parameters. The design of both device types depends heavily on the wave height, length, and period. The designer must know the wavelength of the longest wave to be utilized in an efficient manner in order to size the device properly. The distribution of a wave climate's wave period and height will aid a designer in choosing the proper control techniques and generator. The wave climate will directly affect the other design parameters even if the device is not being tailored to one specific wave climate because the device must react to the physical stresses exerted on it by its surroundings.

Table 3. Important Design Parameters for OWCs and Point Absorbers

OWC	Point Absorber
Wave height, length, and period Chamber dimensions By-pass valve control	Wave height, length, and period Total mean water depth Depth of device below water Length and diameter of float, tube, and/or pump Stroke length

6.0 STATE OF THE ART

The recent signing of the Kyoto Treaty has sparked a renewed emphasis on research into clean alternative energy worldwide. With continued research into the field of wave energy converters, there are many new design developments and enhancements. Europe has made many major contributions to the area, but the US, Australia, and others have also introduced new technology. A discussion of the state of the art in wave energy converters can be divided into the two sections, OWCs and point absorbers, both of which have different subtopics of interest.

6.1 Oscillating Water Column

The OWC design is the most mature wave energy collector in terms of the number and duration of "in-sea" prototypes tested to date. Research on OWCs started in the 1980s in conjunction with their installation in countries such as Japan [9]. The first research topics included air flow control, new turbine designs and turbine control of wave energy absorption, hydrodynamic characteristics, overall design methods, moorings and foundation, and system resonance. These topics still remain at the forefront of OWC research with air flow control and turbine design being the most published.

6.1.1 Air Pressure and Flow Control

A bypass valve is of utmost importance in controlling an OWC application. The bypass valve serves to release extra air pressure caused by waves whose amplitude exceeds normal operating conditions. If this surplus pressure were not released, the turbine would stall. In addition to avoiding stalling, the bypass valve acts to control the rotational speed of the turbine by limiting the flow of air through the turbine. This functionality is similar to blade pitch control for a wind turbine. Moreover, it seems reasonable that pitch control may accompany bypass valves in the future as a method of controlling the turbine speed and excessive air pressure conditions within the chamber, although this idea has not been published.

Typically in research, bypass valves are assumed to allow linear air flow with infinite pressure release ability [23]. In practice, bypass valves are not linear due to air flow turbulence. They also have an upper air flow limit that restricts the rate at which pressure may be released [2].

These assumptions are acceptable within limits but will not hold in extreme conditions which are likely to be encountered in an ocean environment. The best way to overcome these limits will be to install valves with larger capacity or multiple smaller valves.

For the sake of analysis, the response time of bypass valves is assumed to be infinitesimal [2]. In reality, the time it takes the valve to respond cannot be neglected. Not only does the valve itself take time to smooth transients, the valve control system takes time to react to changing conditions. The topic of improved response time has not received much attention while control techniques of bypass valves have. Unfortunately, the control method depends on the air chamber dimensions, the turbine and valves used, and wave climate.

The aim of air pressure and flow control should be to improve response time and maximize energy capture. This goal may be achieved using bypass valves but researchers may benefit by looking to the wind energy industry for motivation and new ideas. Ultimately, a universal pressure control technique should be constructed that applies to all OWC applications.

6.1.2 Turbine Design

For the past twenty years, most OWC research has focused on the Wells Turbine, pictured in Fig. 10, as the solution to bidirectional flow. Even though this turbine is not outdated, it may be advantageous to investigate new schemes. Energetech Australia Pty Limited has taken the lead by exploring a new turbine design [9]. While the energy capture efficiency of a rotor prop cannot exceed the theoretical maximum Betz limit of 16/27 or roughly 52% [24], there is room to improve a bidirectional turbine since studies have shown that rotor blade sections specially designed for a Wells Turbine increases the efficient operating range [23]. Once again, the procedures for wind turbine blade design in a variable speed environment may be cross-applied to this situation.

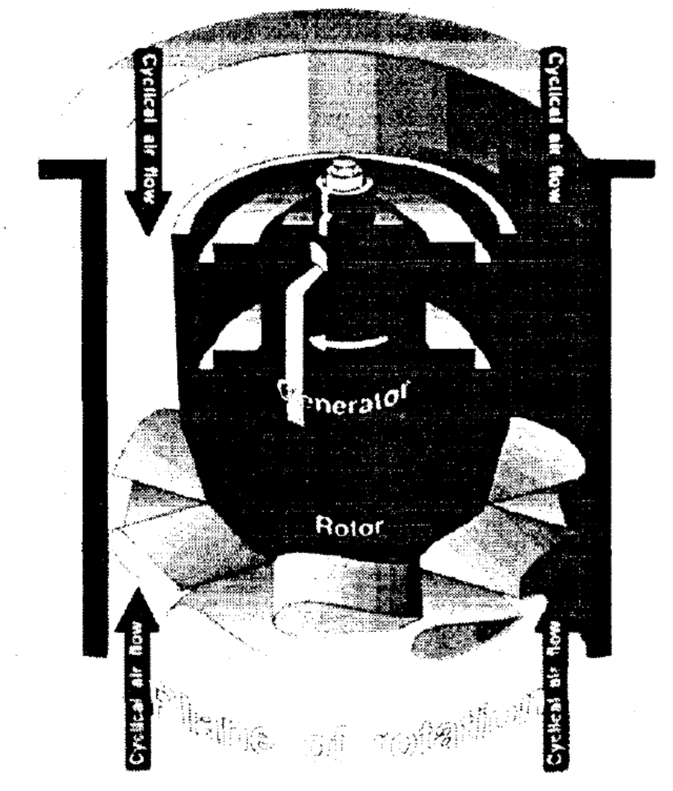

Fig. 10 Uni-directional Wells Turbine [8]

6.1.3 Moorings and Installation

As wave energy advocates should know, the potential locations for shoreline OWCs are limited. This opens the door to deep water or near shore OWC installations. The restricting factor in this case is that the installation of such devices is complex and expensive [9]. Special moorings (foundations) are needed to keep the device safely situated during the worst weather conditions. The foundation must provide the proper balance between slack and rigidity so that the OWC is not jerked around but may also move in response to intense wave crests so as to dissipate the impact [9, 11]. At the same time, the cables used to attach the OWC to the foundation must be sturdy and impervious to the harsh underwater climate. These issues should be faced with an emphasis on economical solutions so that an effective and less costly installation process is developed.

6.2 POINT ABSORBER

The point absorber idea has been around as long as the OWC but has received less attention until now. Actually, the point absorber has overtaken the OWC as a commercial device in the US [17]. Many of the same problems that the OWC encounters are also seen with the point absorber such as moorings and foundations. The point absorber must also cope with a control strategy to bring the device's motion in resonance with the waves so as to maximize energy capture while limiting movement when encountering extreme wave conditions [11]. Akin to the need for new bidirectional turbine designs for the OWC, new power take-off methods for the point absorber need to be studied. Both the power take-off and control strategies have garnered considerable research interest recently.

6.2.1 Control Techniques

The control strategy employed depends heavily on the type of device being operated, yet the same methods and principles underlie all device types. The device should oscillate with the same frequency as the over passing waves through some means of damping. The damping may come from buoyancy tanks or the physical resistive force of a generator [1, 3]. The methods for controlling generator damping are well known, but the methods for controlling the oscillation of a point absorber by means of buoyancy tanks calls for improvement. The main problem with buoyancy control is the time required to either pump air or seawater into tanks as is conventionally done to alter the buoyancy of underwater devices [19]. To overcome these time constraints, the point absorber should predict future wave conditions rather than react to present conditions. This would require predictive algorithms based on data collected from sensors strategically placed around the point absorbers. Current research has focused on solving these types of prediction problems [20]. The obstacles facing researchers are breaking down the three dimensional nature of wave movement and applying it to control of the point absorber. In practice, the buoyancy tanks should be used for large scale oscillation control while generator damping could counteract transient forces [3, 4].

The use of meteorological data from an organization such as the National Weather Service could be used in conjunction with the sensors to prepare the point absorbers for severe weather as well. In the case of dangerous weather, the point absorbers may be sunk to a safe depth to ride out a storm. On the other hand, if damage to the point absorber is not expected, the damping may be increased to limit stroke length – the distance the point absorber pumps up and down – during a storm.

6.2.2 Power Take-Off Methods

Designers face the task of selecting a power take-off method to convert the linear motion of a point absorber to electrical energy. The conversion method must take into account that the linear forces transferred to the point absorber can exceed 1 MN with velocities of 2.2 m/s [3]. Typically, this conversion process involves some intermediary to convert linear motion to the rotary motion needed to run a conventional electric generator. The most popular and widely-used intermediary is a hydraulic system. Conversely, linear generators or magnetohydrodynamic (MHD) generators can directly convert the point absorber's linear motion to electrical energy. Another power take-off approach involves a contact-less force transmission system. There is no consensus on which method is best, and each has its pros and cons based on the designer's criteria.

6.2.2.1 Hydraulic System

The hydraulic system in a point absorber consists of a piston, a hydraulic pump, and a hydraulic motor. The linear wave motion acts to move the piston up and down which pumps pressurized hydraulic fluid through the hydraulic pump. The pump then feeds the hydraulic motor. This motor creates the rotary motion needed to drive a standard electric generator, and by coupling the hydraulic motor to a generator, the conversion process is complete.

Hydraulic systems have advantages and disadvantages. The hydraulic power take-off method is mechanically inefficient [9]. Because the conversion process is indirect, losses occur during pumping and turning the hydraulic motor in addition to the losses present in the generator and inverter. Another problem is the many moving parts of a hydraulic system. More moving parts means more maintenance issues, and the WECs should be as maintenance-free as possible since access for maintenance will be difficult. Although not all of the hydraulics-based point absorbers use oil as the hydraulic fluid (some use seawater), it should be well noted that a broken seal or valve could leak oil. Also, hydraulic systems are designed to work at speeds lower than those experienced by a WEC which are typically on the order of 2 m/s [5].

Some companies prefer hydraulics over direct drive systems. A central reason is that hydraulic systems have a proven track record and most engineers are well versed in their use as opposed to direct drives. Furthermore, hydraulic systems are usually less expensive to design and build than direct drives [11]. If hydraulics are to succeed, research should be undertaken to improve efficiency and performance at low speeds and to develop better hydraulic fluids for undersea use.

6.2.2.2 Linear Generator

Linear generators are like conventional rotary generators in that they convert mechanical energy to electrical energy; however, the rotor in a linear generator – usually referred to as a 'translator' in this application [4] -- moves in an up and down fashion as opposed to the rotational motion of a traditional generator's rotor. The benefit of the linear generator is that it directly converts wave motion into electricity rather than relying on gearboxes and hydraulics as intermediaries. Thus, it has fewer moving parts and is more efficient than a hydraulic system. The drawback to using a linear generator is that it must be specially tailored to fit the specifications of a WEC and so is not something that can be bought off-the-shelf like a hydraulics-based system. This makes using linear generators a more expensive option. Nevertheless, costs can be minimized through mass production.

There has been a bustle of activity surrounding linear generators for WEC applications in the past few years. The main topic is dedicated to analyzing different linear generator topologies to classify the ones best suited for a point absorber. A cursory comparison has been made between

- permanent magnet (PM) synchronous
- induction
- switched reluctance
- longitudinal flux PM (LFPM)
- and transverse flux PM (TFPM)

machines [4, 5]. For a WEC application, there are several criteria that differentiate these machines from each other. One of the more important criteria is the amount of shear stress that the machine can provide to offset the high forces at low speeds experienced by direct drives in WECs, and by virtue of design, a physically large machine is needed [4]. The reciprocating force of a machine is coupled to its size, which should be minimized while providing the necessary force. Other comparative criteria include cost, efficiency, and durability.

Out of all the machines listed, the TFPM pictured in Fig. 11 is considered the most suitable for the direct drive of a point absorber [4, 5]. It has the best efficiency and is also the smallest because of its high shear stress density. The PM synchronous machine may also be considered as an alternative to the TFPM, but the TFPM is considerably more efficient [4]. While a TFPM is costly, it is still slightly cheaper than the PM synchronous.

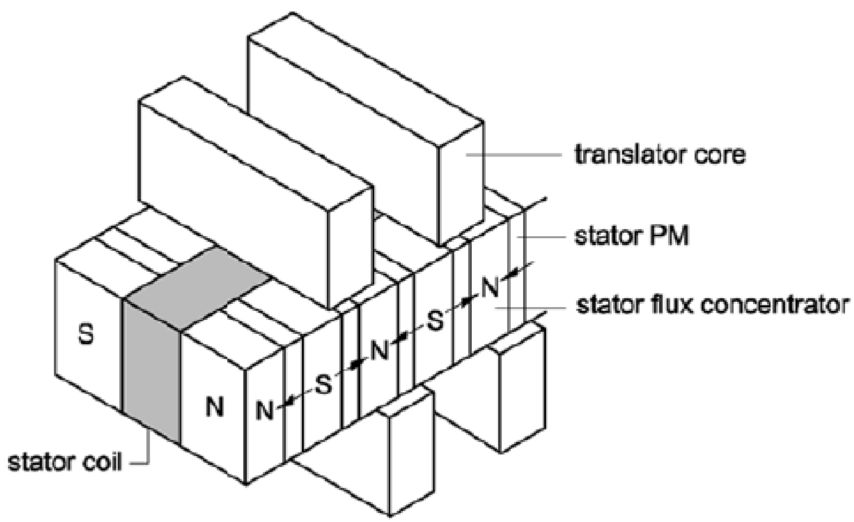

Fig. 11 TFPM Machine with Flux Concentration and Stationary Magnets [4]

Despite the advantages of using TFPMs in point absorbers, they have a few setbacks that will need further research consideration. As mentioned, the TFPM supplies more shear stress than the other machines listed, with levels ranging from 20 – 40 kN/m^2, and so can provide 1 MN of reactionary force [4]. The problem with providing so much shear stress by means of neodymium-iron-boron (NdFeB) permanent magnets is the substantial attractive forces between the stator and translator. The bearings suffer dangerous loads as a result and thus become a maintenance concern. To balance the attractive forces between the stator and translator, a double-sided stator may be used – as opposed to a single-sided stator where the windings are placed on one side [4, 5]. Despite better balance with a double-sided stator, deviations in the air gap still occur with the consequence of severe bearing loads. It may be beneficial to look into triple or quadruple-sided stator windings for the TFPM to alleviate these problems.

6.2.2.3 Magnetohydrodynamic Generator

The magnetohydrodynamic (MHD) generator is also a direct drive mechanical/electrical converter. To date, there is only one company, Scientific Applications & Research Associates (SARA) Inc., employing this method, and depending on their success, others may follow suit. Unlike other MHD generators, SARA's MHD generator works on the principle that flowing seawater can conduct electric current in the presence of a strong magnetic field. Over passing waves induce seawater to flow through a hollow tube with flared inlet and outlet sections which boost water velocity by means of the Bernoulli principle. Electromagnets or other mechanisms such as super conductors generate a magnetic field perpendicular to the flow of water. The strong magnetic field stimulates an electric current in the passing seawater which is collected by electrodes placed in the tube [12].

This conversion method is highly desirable due to the lack of moving parts. It may be harder to sell industry on the MHD idea since it has not been extensively used or studied. Consequently, SARA Inc. is working to create a 50 – 100 kW MHD unit with the help of money from the US Dept. of Energy.

6.2.2.4 Contact-less Force Transmission System

The contact-less force transmission system (CFTS) proposed by Oregon State University is one solution to the problem of designing a system that can withstand severe weather since there is no mechanical link between the float and the power take-off. In this buoy type system, pictured in Fig. 12, a magnetic field between the piston's permanent magnets and the iron cylinder attached to the float acts as the intermediary, creating a reluctance force. The difference between the CFTS and a linear generator is the use of a ball screw and ball screw nut combination to convert the linear motion of the piston containing the permanent magnets to rotary motion for use in a rotary generator. The current prototype can produce 50 W of peak power [26].

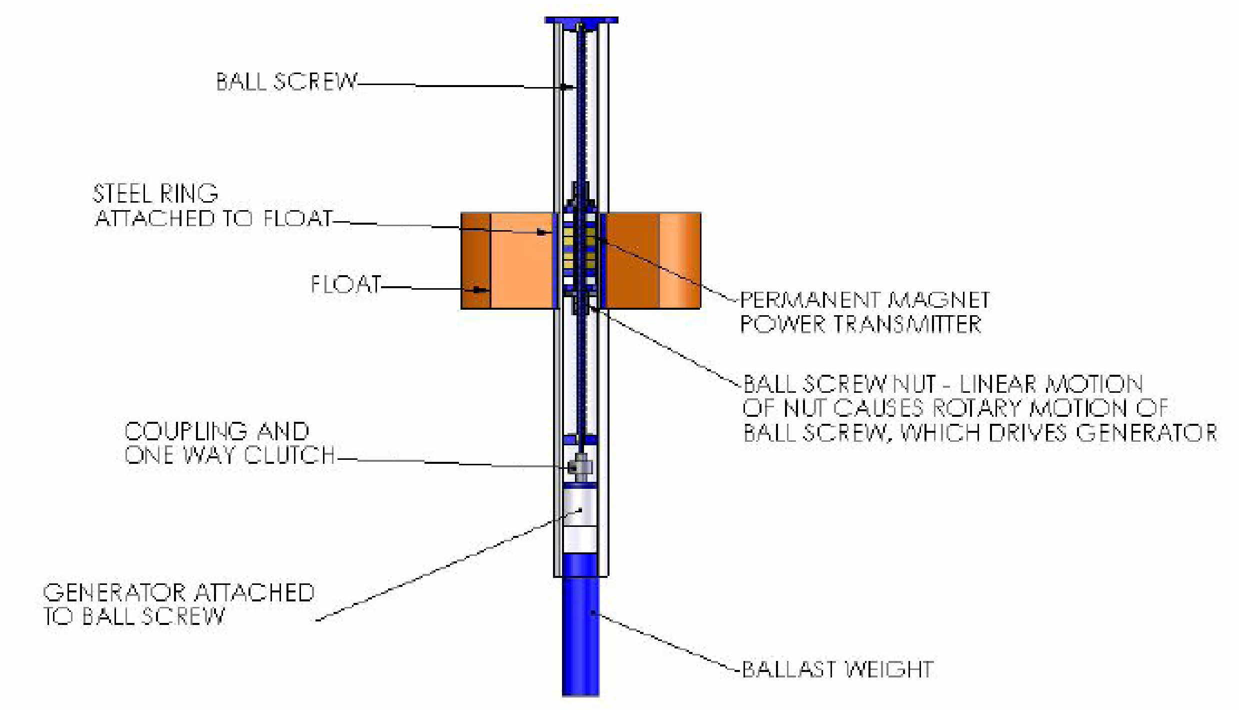

Fig. 12 Contact-less Force Transmission System [26]

7.0 PROPOSED FUTURE RESEARCH FOCUS FOR ALL WECs

Some areas of research would benefit all WEC types. For example, developing high pressure underwater electrical cables with improved flexibility and strength would increase the reliability of every wave and offshore wind energy farm. With regards to power electronics, constructing an inverter especially for WEC applications would enhance operation. Since waves are irregular in direction and size, induced voltages in the generator vary in magnitude and frequency. Thus, the power developed by any of the wave energy converters will be irregular. For this reason, an inverter is needed to smooth the output power and correct the power factor. Current research simply states that voltage source inverter control surpasses current source inverter control for better efficiency and power factor [3]. In addition to maximizing power output and stabilizing grid connections with the inverter, the WEC might require a bidirectional inverter to provide power back into the machine for electrical damping. The damping supplied will allow operation closer to the resonant wave frequency [5].

Another area of interest is the hydrodynamic response of wave energy converters and their influence on the surroundings. When laying out a wave energy farm, how the wave climate changes when the WECs are introduced and how the WECs affect each other will need further investigation. This type of research is currently being undertaken [27] with the conclusion that such simulations require significant computational effort. Table 4 summarizes other research topics needed in the field of wave energy.

Table 4. Wave Energy Research Topics

Wave Energy Research Topics		
Mechanical	*Electrical*	*Other Areas*
Hydrodynamic characteristics Indirect power take-off methods Mechanical reliability Long term fatigue of: ● Moorings ● Foundation ● Anchorage Mechanical maintenance Installation	Direct power take-off methods Power conversion Power controls Power transmission Electrical reliability Electrical maintenance Grid connection requirements	Weather forecasting for real-time wave behavior Navigating around devices Standardized testing of devices Cost effective: ● Waterproofing ● Corrosion resistant materials ● Offshore access

8.0 ENVIRONMENTAL IMPACT

There are several environmental consequences to weigh before installing wave energy converters. Each type of WEC poses different environmental risks as seen in Table 5. The main difficulties involve the consequences to sea life and ship navigation [10]. Wave energy developers will need to address methods to mitigate as many of the negative environmental impacts before wave energy is an acceptable method of energy production. Additionally, governments should develop a standard procedure to assess any proposed wave energy farms.

Table 5. Environmental Impact of Wave Energy Converters

Environmental Impact (X = possible impact, XX = more impact than other device)			
Problem Area	*Impacts*	*Point Absorber*	*OWC*
Animals	Underwater noise emissions	X	X
	Above water noise emissions		X
	Accidents:		
	● Animal collisions with device	X	X
	● Animals swept into chambers		X
	Food chain changes due to change in environment	X	X
	Electromagnetic fields and vibrations affect mammal sonar and fish reproduction	X	X
	Sedimentation and turbidity around device affects fish reproduction	X	XX
	Unnatural reef (possibly desirable)	X	X
Fauna and Seabed	Loss of seabed due to cabling and structural foundation	X	XX
	Sedimentation structural changes	X	XX
	Fauna changes due to foundation/hard substrates	X	XX
	Fauna influenced by electromagnetic fields	X	X
Coastline	Current and sediment changes for shoreline devices		X
	Decreased shoreline wave intensity due to offshore devices (possibly desirable)	X	X
Visual Impact	Above water visual intrusion		X
Pollution	Oil leakage	X	X
	Debris from ship collisions	X	X

9.0 CONCLUSION

Both ocean wave power and the associated power take-off devices currently being investigated have been presented along with wave energy research topics. The pros and cons of all conversion methods with related environmental impacts have also been discussed. While both the OWC and point absorber design have promise, the point absorber may be less obtrusive since it resides below the ocean surface. For the same reason, the point absorber is less likely to be damaged during a storm. Future research may improve the durability of offshore OWCs so that their resilience to storms improves. Regardless, both of these devices continue to improve, and some predict the amount of ocean energy utilized will increase dramatically with recent developments in ocean energy extraction as discussed above [9, 11].

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APPENDIX A – WAVE ENERGY COMPANIES

Company Name	Product	Special Notes	Base Location	Projects	Website
374's Electric Power Corporation	Ocean Surf Energy Systems		Stoughton, MA		www.374electric.com/welcome.htm
ABS Alaskan	Small water generators (micro-hydro turbines)	Alternative energy and remote power products	Fairbanks, AK	Residential consumers	www.absak.com
Aqua Energy Group, Ltd.	"AquaBuOY" Wave Energy Converter	Point-absorber incorporating a hose-pump which uses water as the hydraulic fluid	Mercer Island, WA	1MW Power Plant - Clallum County Public Utility (Makah Bay, WA)	www.aquaenergygroup.com
Float Incorporated	"Pneumatically Stabilized Platform" (PSP)	Floating Ocean Real Estate - uses an OWC to extract energy from waves	San Diego, CA		www.floatinc.com
Florida Hydro Power and Light Company	Offshore Gulf Stream Current Energy		Palatka, FL		www.floridahydro.com
GCK Technology, Inc.	"Gorlov Helical Turbine"	Power take-off for ocean and tidal currents: rotates in same direction regardless of water flow direction, received Edison Patent Award	San Antonio, TX		www.gcktechnology.com/GCK
Hawaii Energy Dept.	Ocean Thermal Energy Conversion (OTEC Energy)		Honolulu, HI	5MW Pre-Commercial Plant	www.hawaii.gov/dbedt/ert/bib/bib_otec.html
HydroVenturi	"Rochester Venturi"	Tidal current electrical generation: no moving mechanical or electrical parts underwater, water flow pressure reduction brings in air which is used to generate electricity	San Francisco, CA	60kW Demo Unit North of England	www.hydroventuri.com
Independent Natural Resources, Inc. (INRI)	"SEADOG Pump"	Point-absorber incorporating a piston for pumping water or air into a turbine	Eden Prairie, MN	1/32-scale prototype was tested in the wave tank of Texas A&M University	www.inri.us
Kinetic Energy Systems	"Hydrokinetic Generator", "KESC Bowsprit Generator", "KESC Tidal Generator"	Tidal current energy: meant for flood and ebb tides, 600kW with products ranging 35%-65% efficiency	Ocala, FL		www.kineticenergysystems.com
Marine Development Associates, Inc.	OTEC		Saratoga, CA	Project RATAK: 5-10 MW OTEC for the Gov't of the Marshall Islands; OTEC Development Plan Review for Gov't of Taiwan; Assessment for Philippine Gov't; MDA's Island Nation OTEC Program	www.marinedevelopmentinc.com/ocean_energy.htm
Marine Innovation & Technology	Ocean Current Farm		Berkeley , CA		www.minifloat.com/ocean.htm
Mo-T.O.P.S Oceanic Power Systems	"Wind Goose"	OTEC variant	Del Rio, TX		www.isfind.com
OCEES, International- Ocean Engineering and Energy Systems	OTEC		Honolulu,HI		www.ocees.com/mainpages/otec.html
Ocean Motion International LLC (OMI)	"WavePump"	Point absorber array whose buoys pump seawater through a hydro-turbine generator as it descends in a wave trough	Colorado and Oregon	Functioning 1/20th scale model of new OMI WavePump design is unveiled in Dana Point, CA (June 2002); OMI submits application to Hawaii Renewable RFP (April 2004), submits application to present investment opportunity at the November 2003 NREL Industry Growth Forum	www.oceanmotion.ws
Ocean Power Technologies, Inc.	"PowerBuoy"	Near Shore Wave Energy Point Absorber: passed the rigorous Environmental Assessment process to install units in Hawaii, Initial Public Offering (IPO) AIM Market of the London Stock Exchange ("AIM-OPT") on October 31, 2003	West Trenton, NJ; VIC, Australia	Partnering with Iberdrola S.A. in Spain and Total in France; Partnering with US Navy in Hawaii; Contracts with Lockheed Martin Corp. and New Jersey Board of Public Utilities	www.oceanpowertechnologies.com
Ocean Wave Energy Company	"Ocean Wave Energy Converter"	Completed bench top trials with full size components under a Small Business Innovation Research contract from the US Coast Guard	Bristol, RI		www.owec.com
Ocenergy	Near Shore, Offshore Wave Energy for Hydrogen Production		Norwalk, CT		www.ocenergy.com
ReEnergy Group PLC ("ReEnergy")	"Oases"	Uses wave power generation technology as a cost effective method for desalination	UK (US: San Diego, CA)	Contracts in Mexico, California, Peru and Morocco	www.renergypacific.com
Scientific Applications & Research Associates (SARA) Inc.	Point Absorber with Magnetohydrodynamic Generator	Magnetohydrodynamic (MHD) Generator; Almost no moving parts. No gears, no levers, no turbines, no drive belts, no bearings, etc.	Huntington Beach, CA	DOE contract Phase II SBIR Program: design, construct, and demonstrate a 50-100 kW MHD unit	www.sara.com/energy/WEC.html
Sea Solar Power International	OTEC	University of Maryland tests confirm heat transfer with 3.4% total cycle efficiency (perfect Carnot Cycle efficiency is 7.4%)	Baltimore, MD		www.seasolarpower.com
SeaVolt Technologies	"Wave Rider"	Near Shore Point Absorber: uses hydraulics for power take-off	Berkeley, CA		www.seavolt.com

Tidal Electric, Inc.	Tidal Lagoons	Uses a rubble mound impoundment structure and low-head hydroelectric generating equipment situated a mile or more offshore in a high tidal range area. Shallow tidal flats provide the most economical sites	West Simsbury, CT; Anchorage, AK; London, UK	60 MW Swansea Bay project, UK: measures 5 km^2 in area and about a mile offshore; project agreement with Liaoning Province, China	www.tidalelectric.com
UEK Corporation	"Underwater Electric Kite"	Hydro kinetic turbines for Current, Tidal, OWC Energy; no dams or impoundments required since no foundation is necessary	Annapolis, MD	DOE contract SBIR/DOE DE-FG02-00ER82930; Contract with Ontario Power Generation to test the hydro kinetic 'Twin Turbines'	uekus.com
Verdant Power	Instream Energy Generation Technology (IEGT)	Tidal Current Energy: free-flow hydropower technology or kinetic hydro energy systems	Arlington, VA	In conjunction with GCK Technology, 1MW Tidal Site at Merrimack River, MA. Uses GCK's Gorlov Helical Turbine; Testing in the Potomac River, Carderock, MD; Prototype in New York City's East River	www.verdantpower.com
Wader, LLC	Hydrocratic Generator	Salinity Gradient Energy	Laguna Beach, CA		www.waderllc.com
Seapower Pacific Pty. Ltd. (Shareholders: Renewable Energy Holdings Plc (REH) - UK; Pacific Hydro Ltd. - Australia; Carnegie	"CETO" Wave power converter	Near Shore Point Absorber: wave crests depress a disk which delivers pressurized water to shore where energy conversion takes place	West Perth, Western Australia	100kW in-sea prototype, 2005	www.carnegiecorp.com.au/Operations/Renewable_Wave_Energy_Project_2004.html
Blue Energy Canada	The Davis Turbine (Vertical Axis Turbine for Tidal Currents)	Proof of Concept Review: US Army Corps of Engineers, the National Research Council of Canada, et al - RW Beck (Engineering) Inc., Sept 2005	Alberta, Canada	Proposed tidal energy project for Scotland's Pentland Firth	www.bluenergy.com
Wavemill Energy Corp.	"Wavemill"	shoreline and near shore applications with patented suction chamber and enclosed, surge wall	Dartmouth (Halifax), Nova Scotia, Canada	August 2001: scaled model of the ESW Wavemill®	www.wavemill.com
China New Energy (CNE)	Tidal Energy, Ocean Current, Wave Energy, Thermal Energy, Salinity Gradients	CNE is a non-profit research network founded by Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences, while jointly under the direction of State Ministry of Science & Technology, State Economic & Trade Commission and Chinese Academy of Sciences	Guangzhou, China		www.newenergy.org.cn/english/ocean/index.htm
Wave Dragon	"Wave Dragon"	Overtopping wave energy converter uses large collector arms to funnel water to a Kaplan turbine which turns a PM generator	København, Denmark	January 2005: 20 kW Wave Dragon prototype taken offline after one year and nine months of continuous real sea testing	www.wavedragon.net
WavePlane Production A/S	"WavePlane"	Overtopping wave energy converter uses a fly-wheel-tube for power take-off	Gentofte, Denmark	September 2002 to April 2003: WavePlane underwent 3:10 sea tests in Japan by NKK	www.waveplane.com
DAEDALUS Informatics	"WECA" (Wave Energy Conversion Activator)	20kW OWC device	Athens, Greece		www.daedalus.gr
Hydam Technologies Ltd.	"McCabe Wave Pump (MWP)"	Point absorber with two rectangular steel pontoons which move in relation to a stationary central raft. The hinges of the pontoons drive a hydraulic power take-off system.	Kerry, Ireland	Has received funding from the Irish Marine Institute	n/a
Clearpower Technology Ltd. (also listed as Wavebob Ltd. and duQuesne Environmental Ltd.)	"Wavebob"	Self-reacting point absorber that extracts power from the relative movement of two floating bodies that have different heave frequency responses. This property enables the Wavebob to utilize energy from more wave frequencies than conventional single buoy point absorbers.	Dublin, Ireland	1/50th and 1/20th scale tests conducted at the Hydraulics and Maritime Research Centre (UCC, Cork) and the large wave channel of the German Coastal Defence Centre (Hanover University and the Technical University of Braunschweig)	www.clearpower.ie
National Institute of Ocean Technology (NIOT)	"Backward Bent Ducted Buoy (BBDB)"	OWC device with variable resistance induction generator	Vizhinjam, Kerala (India)	1/13 prototype gives air power / wave power conversion above 60% (started Dec. 1990 with improvements added over time)	www.niot.res.in/m1/Wave.htm
S.D.E. Energy Ltd.	Offshore wave energy	OWC / Overtopping device works by forcing waves into cavity separated from hydraulic oil by membrane. Incoming waves pressurize the oil which drives a hydraulic generator.	Tel Aviv, Israel	Israeli government has authorized S.D.E. to produce and sell 4MW of electricity for 20 years, at 5.25 cents per kWh. Project is approved with partial financing by the Chief Scientist of Israel.	www.sde.co.il
JAMSTEC	"Mighty Whale"	OWC device with three induction generators	Yokosuka, Japan	28 March 1998: deployment of 110 kW prototype at Gokasho Bay, Japan funded by Japan's Science and Technology Agency	www.jamstec.go.jp/jamstec/MTD/Whale
Ecofys	"Wave Rotor"	Orbital currents in waves and tidal currents induce hydrodynamic lift which turns a set of blades around a vertical axis	Utrecht, The Netherlands	Oct. and Nov. 2004: 1/10 scale model tested at NaREC in Blyth (0.5 MW model to be installed in UK)	www.ecofys.com

Neptune Systems	Magnetohydrodynamic (MHD) generator in a buoy wave energy converter and tidal current energy converter	Uses a 20 m diameter superconducting magnet solenoid (SMES) which produces a magnetic field strength of 5 Tesla with energy content ~100 GJ. The tidal generator can deliver 4 MW power installed at a 3 m/s tidal current velocity.	Breda, The Netherlands		www.neptunesystems.net
Hammerfest Stroem AS	"Tidekraft"	Underwater turbine props similar to wind turbine props collect tidal current energy	Hammerfest, Norway	25 Sept. 2005, 'The Blue Concept' project: prototype installed at Kvalsundet producing 21 GWh per year	www.e-tidevannsenergi.com
Ing Arvid Nesheim	Point absorber	Absorbs energy from vertical, pivotal, horizontal backwards and forwards (to-and-fro) motion via a hydraulics system	Vollen, Norway		www.anwsite.com
WAVEenergy AS	"Seawave Slot-Cone Generator (SSG)"	Overtopping wave energy converter with multi-stage turbine (MST)	Norway	Has received funding from the European Commission FP-6-2004-Energy-3 (7 Apr. 2005) and the Norwegian Research Council to develop the MST turbine (25 Jan. 2005)	www.waveenergy.no/index.htm
Sea Electrical Generators, Ltd.	Point absorber	Made from cheap recycled plastic (polyethylene, polypropylene), meant to be replaced every five years	Russia		easy-energy.iatp.org.ua
Vortex Oscillation Technology, Ltd. in partnership with The Engineering Business Ltd. (Northumberland, England)	"Stingray"	Oscillating wings extract energy from tidal currents	Moscow, Russia	2004: 5 MW installation off the coast of Scotland	www.vortexosc.com/index.php, www.engb.com
Yakov Kolp	"Sea Wave Energy Converter (SWEC)"	Wave oscillation generator with capacity from kilo to megawatt range	Russia		www.rvf.ru/engl/expo-yakor.php
Seabased Energy AB	Point Absorber with Linear Generator	Linear permanent magnet generator with large number of poles and NdFeB magnets that allow for high magnetic excitation with smaller magnets	Uppsala, Sweden	Working with the Division for Electricity and Lightning Research at Uppsala University, Sweden	www.seabased.com
Sea Power International AB	Overtopping wave energy converter	Near shore WEC	Stockholm, Sweden		www.seapower.se
Naturalist Wave Power Plant AB	Hydraulic-based offshore WEC	Waves rotate joints of chassis which pressurizes mineral oil. This drives a hydraulic generator.	Ankara, Turkey		www.dalgaenerjisi.com/ana-english.asp, www.wipo.int/pctdb/en/fetch.jsp?LANG=ENG&DBSELECT=PCT&SERVER_TYPE=19&SORT=1149288-KEY&TYPE_FIELD=256&IDB=0&IDOC=630415&ELEMENT_SET=IA,WO,TTL-EN&RESULT=1&TOTAL=1&START=1&DISP=25&FORM=SEP-0/HITNUM,B-ENG,DP,MC,PA,ABSUM-ENG&QUERY=wo%2f02075151
AWS Ocean Energy Ltd.	"Archimedes Wave Swing"	Air-filled, submerged point absorber uses a linear generator. Wave crests depress the device, and troughs force it upwards.	Ross-shire, England	24 May 2004: 2MW installation of prototype off of Portugal	www.awsocean.com, www.waveswing.com
Embley Energy Ltd.	"Sperboy"	Floating buoy with multiple oscillating water columns of different lengths to utilize a larger range of wavelengths	England	The Carbon Trust is evaluating the Sperboy through their Marine Energy Challenge programme	info@sperboy.com, www.thecarbontrust.co.uk/ctmarine2/Page1.htm
Marine Current Turbines, Ltd. (MCT) and IT Power	"SEAFLOW" marine current turbine	Tidal currents drive two blades around a horizontal axis like an underwater wind turbine	Hampshire, UK	31 May 2003: The Carbon Trust sponsors construction of a 300kW experimental turbine 3km offshore from Lynmouth, Devon, 2003-3-122-1-2	www.itpower.co.uk, www.marineturbines.com
Ocean Power Delivery, Ltd.	"Pelamis"	Near shore cylindrical structure whose hinges drive hydraulic motors as the power-take off	Edinburgh, Scotland, UK	2.25MW Prototype: three Pelamis P-750 machines located 5km off the Portuguese coast	www.oceanpd.com
ORECon Ltd.	"MRC" System	Multiple oscillating water column	Plymouth, UK	June 2005: FEED for a 2MW pre-production prototype	www.orecon.com
Offshore Wave Energy Ltd. (OWEL)	"Grampus"	Long inlets trap and compress the air in wave troughs. Reservoirs accumulate the compressed air which drives a turbine.	Portsmouth, UK	Future project: tank-testing 18 metre long physical model	www.owel.co.uk
The Wave Power Group at the University of Edinburgh	"Salter's Duck" and "Sloped IPS Buoy"	Both are point absorbers using hydraulics power take-off	Edinburgh, Scotland, UK	Salter's Duck project no longer funded, Sloped IPS Buoy applying for EPSRC programme funding	www.mech.ed.ac.uk/research/wavepower/index.htm
Wavegen	"LIMPET"	Shoreline OWC	Northumberland, England	June 2004: first generation of Breakwater Turbine installed on the Limpet plant	www.wavegen.co.uk