Ocean Wave Energy Conversion – A Survey

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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 paper gives a systematic and comprehensive overview of 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, current state-of-the art, and further research areas. Thereby, the paper seeks to enhance investigation of results obtained in other fields in the ocean wave energy conversion setting and to stimulate research on topics that have not been in the focus so far.**

Keywords—ocean renewable energy, wave energy conversion

I. 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. Ocean energy comes in a variety of forms such as geothermal vents, and ocean currents and waves. The most commercially viable resources studied so far are ocean currents and waves which have both undergone limited commercial development. Estimates conclude that marine and tidal currents combined contain about 5 TW [1] of energy, on the scale of the world's total power consumption. There is approximately 8,000-80,000 TWh/yr or 1-10 TW of wave energy in the entire ocean [1] and wave energy provides "15-20 times more available energy per square meter than either wind or solar" [2].

This paper does not focus on ocean current energy converters because their technology is already mature compared to wave energy converters, and ocean current energy resources are only briefly discussed for completion (Section II.A).

The potential of wave energy to become a fully commercially developed energy resource is highlighted by the following two quotes.

> *"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."* [2]

> *"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)."* [2]

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.

The structure of this paper follows the design process of a wave energy converter (WEC) and then addresses future research interests. First, the paper provides an overview of ocean energy resources (Section II) and then calculates WEC sizes based on the wave energy present (Section III). Following this, classifications, characteristics, and state-of-the-art in wave energy converters are presented (Section IV). Subsequently, WEC design aspects, associated environmental concerns and common WEC research topics are investigated (Section V). Then, areas of further research are identified (Section VI). Thereby, the paper seeks to enhance investigation of results obtained in other fields in the ocean wave energy conversion setting and to stimulate research on topics that have not been in the focus so far.

II. OCEAN ENERGY RESOURCES

A. 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, speeding up and slowing down over about a ten year period in what is known as the thermohaline cycle [3].

Tidal currents are different than marine currents in that 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 [1]. 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. 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.

B. Wave energy

Ocean waves arise from the transfer of energy from the sun to wind and then water. Solar energy creates wind which blows over the ocean, converting wind energy to wave energy. 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 [4], 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. As stated earlier, there is approximately 8,000-80,000 TWh/yr or 1-10 TW of wave energy in the entire ocean [1], and on average, each wave crest transmits 10-50 kW/m.

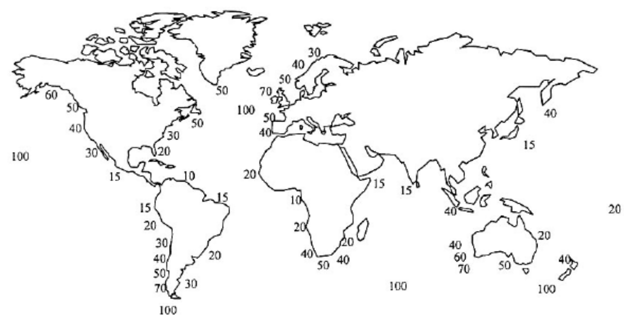

Fig. 1: Approximate global distribution of wave power levels in kW/m of wave front, used with permission from [5].

C. Wave climate

In order to assess an area for wave energy development, the wave height and length distributions and total mean water depth should be surveyed. These parameters define the wave climate from which the area's wave power levels can be computed. In general, the waves present on the western edge of the continents contain more energy because of the west-to-east winds [Fig. 1]. Moreover, the power carried by waves decreases as they reach the shore due to frictional losses with the coastline. It should also be noted that average wave power is cyclical with winter bringing energy levels up to six times greater than summer [6].

III. Wave Energy Calculations

A. Introduction

Calculating the forces acting on a device and the available wave power are important for the design process of a wave energy converter (WEC). Both must be known in order to size a WEC according to the desired energy output. This section explains the fundamentals of such calculations so as to illustrate the different principles, parameters involved, and their orders of magnitude.

B. Wave energy and power

Table I and Fig. 2 summarize a commonly used wave energy nomenclature [7] that is also used here.

TABLE I
WAVE NOMENCLATURE [7] (ILLUSTRATION: FIG. 2)

Name	*Description*	*Units/Value*
SWL	mean *s*ea*w*ater *l*evel (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/s
λ or L	wavelength = $gT^2/(2\pi)$	m
ρ_{water}	sea water 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

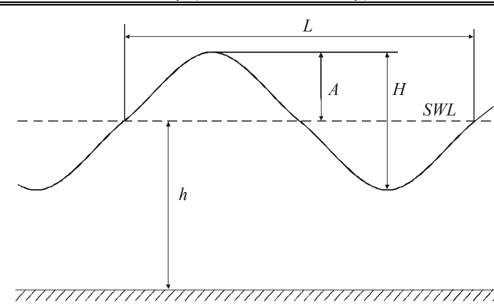

Fig. 2: Wave nomenclature based on [7].

Energy and power density: The energy density of a wave is the mean energy flux crossing a vertical plane parallel to a wave's crest (1). The energy per wave period is the wave's power density and can be found by dividing the energy density by the wave period (2) [7, 8].

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

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

Power per meter of wave front: A wave resource is typically described in terms of power per meter of wave front (wave crest). This can be calculated by multiplying the energy density by the wave front velocity (3) [7].

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

Figs. 3 and 4 illustrate how wave period and amplitude affect wave power density and power per wave front.

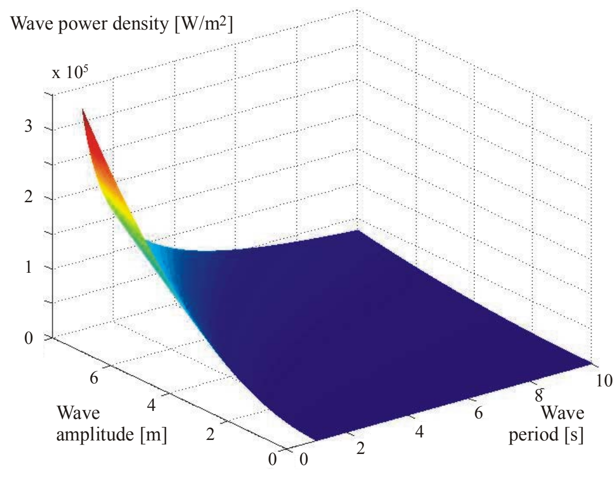

Fig. 3: Wave power density.

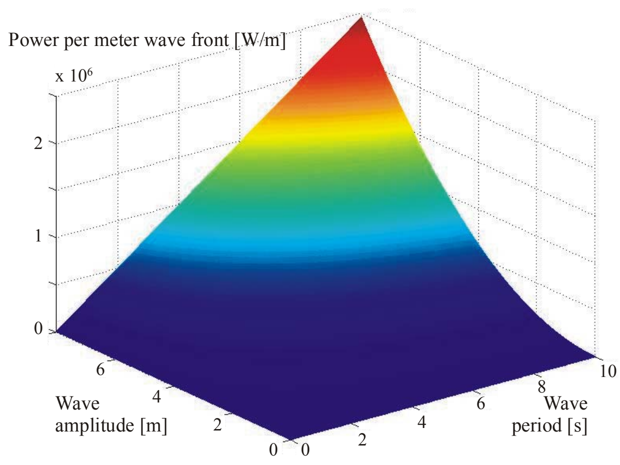

Fig. 4: Power per meter of wave front.

Energy at varying depths: To properly size an underwater WEC, 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 SWL (4) [9]. This property is valid for waves in water with depths greater than $\lambda/2$.

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

C. Power and energy harvested from all directions

The "point absorber" or "buoy-type" class of WECs (Sections IV.D-F) harvests energy from all directions at one point in the ocean.

An underwater float is pushed down when a wave crest approaches and is forced upwards when the wave crest passes (the wave trough approaches). This produces a linear up and down motion corresponding to the change in mass of the overpassing wave. The forces acting on the float may be modeled via Newton's second law of motion. The mass m of water is taken to be $\rho_{water}HA_{float}$, where A_{float} is the area of the float in m^2, and gravity is the accelerating force, a (5). [7]

$$F_{water} = m \cdot a = (\rho_{water}HA_{float})g \tag{5}$$

The power transferred to the float $P_{generated}$ can be calculated by the product of F_{water} and the velocity of the float, which is the stroke length L_{stroke} divided by half the wave period (6). [7]

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

Water passing through a *vertically submerged hollow tube* can drive a piston or hydro turbine and thereby transfer power. This power can be found by calculating the force on the piston $F_{generated}$ (in N) within the tube based on the power to be developed $P_{desired}$ and the length of the piston stroke (7).

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

D. Power and energy from wave induced air pressurization

The "oscillating water column" (OWC) class of WECs (Section IV.B) operates much like a wind turbine via the principle of wave-induced air pressurization. The power available from the airflow through the OWC outlet (9) depends on the airflow speed at the turbine v_{air} (in m/s), the area of the turbine A_{duct} (in m^2), the pressure at the turbine p_{air} (in Pa), and the air density ρ_{air} (in kg/m^3). This power is comprised of two terms: (i) the air flow kinetic energy term, $v_{air}^3A_{duct}\rho_{air}/2$, that is also common to wind turbine analysis, and (ii) the air pressure term, $p_{air}v_{air}A_{duct}$, that is unique to this application [8].

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

IV. Wave Energy Converter Classifications and Characteristics

A. "Wave" as opposed to "flow" energy converters

Ocean energy conversion devices can be classified into "flow" and "wave" energy converters analogous to the two types of ocean energy resources (Sections I and II). Table II breaks down the different ocean energy conversion devices into these two main classes and further subcategories.

TABLE II
OCEAN ENERGY CLASSIFICATION

Ocean flow energy converter		*Ocean wave energy converter (WEC)*	
Tidal currents	*Marine currents*	*Turbine –type*	*Buoy-type*
Tidal lagoon	Bi-directional turbine	Oscillating water column (OWC)	Tube type
Tidal dam	Uni-directional turbine	Overtopping wave energy converter	Float type

As seen from Table II, two fundamental types of WECs are distinguished, although some authors have subdivided these into even more classifications based on their orientation and functionality. The turbine-type was the first to receive attention from the research community, while the buoy-type has received interest more recently. Both have operational prototypes, some of which have been commercialized.

B. Turbine-type WEC – oscillating water column (OWC)

The turbine-type WEC employs a turbine as the energy conversion device. It comes in different forms, the most prominent being the oscillating water column (OWC). The OWC design is the most mature WEC in terms of the number and duration of "in-sea" prototypes tested to date.

Energy conversion in an OWC: The OWC [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. If a turbine is placed on top of the chamber, air will pass in and out of it with the changing air pressure levels. Because of this bidirectional air flow, the turbine must be designed to rotate in only one direction independent of the direction of air flow.

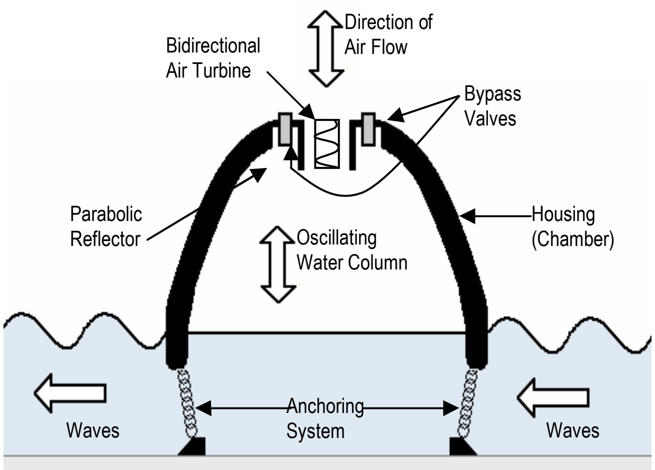

Fig. 5: Offshore oscillating water column device based on [9].

Important OWC design aspects: 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. In addition, the air chamber must also be conducive to air flow through the turbine. This is best achieved with a funnel shaped design (parabolic reflector) such that the chamber narrows from the water surface level to the turbine and concentrates the air flow through the turbine [10]. From (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.

OWC placement – shoreline versus near shore: OWC devices can be placed on the shoreline where the waves break or near the shore. The near shore devices are fixedly moored to the ocean bottom in the same manner as offshore wind turbines or slack moored so as to respond to changes in mean water level (i.e. tides). In general, the wave energy offshore is greater than that at the shoreline, but the installation and maintenance costs increase. In some areas, wave energy concentration near shore through natural phenomena such as refraction or reflection occurs.

Both the near shore and shoreline OWCs are eye sores since they are visible over the ocean surface, so public resistance to their installation can occur with both. The shoreline device will interfere with beachgoers more directly and will therefore be met with the most public resistance.

OWC mooring: Obviously, problems may arise due to the changing mean ocean surface level accompanying the tides with 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. Many tradeoffs exist between the fixedly and slack moored OWCs. For example, 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. Secondly, 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.

OWC state-of-the-art – air pressure and power flow control: A bypass valve is of utmost importance in controlling an OWC application. It serves to release extra air pressure caused by waves whose amplitude exceeds normal operating conditions and thus prevent stalling of the turbine. It also 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. 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 since this idea has not been published as far as the authors know.

Typical to this area of research, bypass valves are assumed to have infinitesimal reaction time and allow linear air flow with infinite pressure release ability [10]. In practice, the time it takes valves to respond cannot be neglected. Plus, 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 [11]. 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 and investigate response time dynamics.

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 research in the wind energy industry may provide motivation and new ideas.

OWC state-of-the-art – turbine design: For the past twenty years, most OWC research has focused on the Wells Turbine as the solution to bidirectional flow. Even though this turbine is not outdated, the wave energy industry may benefit from exploring new schemes. Exploration of a new turbine design has been reported by Energetech Australia Pty. Limited [1]. While the energy capture efficiency of a rotor prop cannot exceed the theoretical maximum Betz limit of 16/27 or roughly 52% [12], 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 [10]. Once again, the procedures for wind turbine blade design in a variable speed environment may be cross-applied to this situation.

OWC state-of-the-art – moorings and installations: Since potential locations for shoreline OWCs are limited, issues affecting deep water and near shore OWC installations are explored. The restricting factor for offshore devices is that installation is complex and expensive [1]. 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 [1, 13]. At the same time, the cables used to attach the OWC to the foundation must be sturdy and impervious to the harsh underwater climate.

C. Turbine-type WEC – overtopping WEC

Energy conversion in an overtopping WEC: The other type of turbine-type WEC device is described as an "overtopping WEC." It works much like a hydroelectric dam. Waves roll into a collector which funnels the water into a hydro turbine [Fig. 6]. The turbines are coupled to generators which produce the electricity. 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 with same issues associated with these mooring options. It should be noted that overtopping WECs are not as common as OWCs.

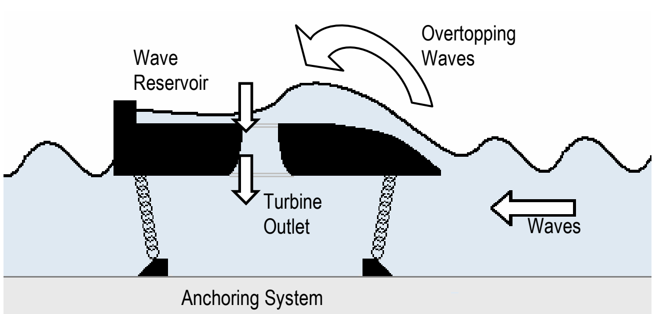

Fig. 6: Overtopping wave energy converter based on [1].

D. Buoy-type WEC

The buoy-type WEC is also known as a "point absorber" (PA) 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 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.

E. Buoy-type tube-type WEC

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. 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 (Section IV.F).

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 the tube, water flows down the tube, and when a wave trough passes above the tube, water flows up the tube. This flow pushes 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 turning 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 [9]. 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. This power take-off method works by means of a piston directly connected to the generator translator (in the case of linear generators, the rotor is referred to as a translator). As a direct-drive system, the up and down movement of the piston directly moves the translator.

F. Buoy-type float-type WEC

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, 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 pressure within the cavity.

The float-type WEC 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 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.

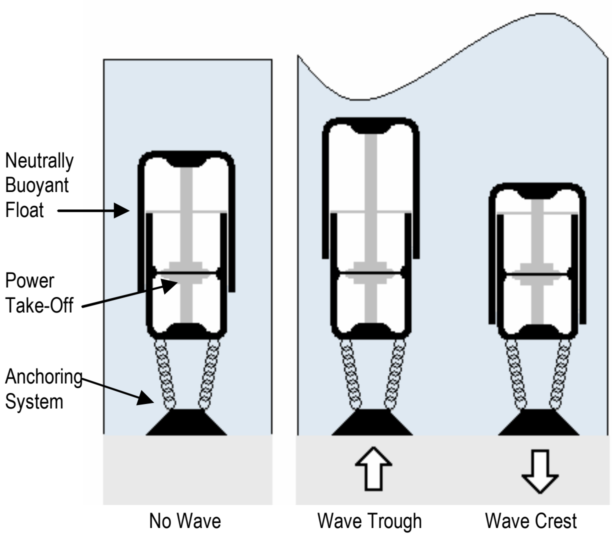

Fig. 7: Below surface point absorber based on [4].

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" [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.

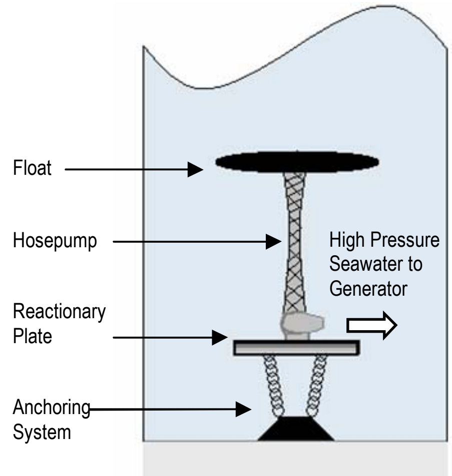

Fig. 8: Hose pump based on [9].

Buoy-type state-of-the-art: 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 overpassing waves through some means of damping. The damping may come from buoyancy tanks or the physical resistive force of a generator [9, 14]. 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 [7]. 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 [4]. 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 [14, 15].

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.

The same statements regarding OWC moorings and installations apply to point absorbers as well.

G. Other forms worthy of notice: the Pelamis

The Pelamis WEC is unique among WECs. 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 [16].

V. Important Factors That Affect the WEC Design

A. Important design parameters

Many of the numerous factors that affect the design of both the OWC and PA-type of WECs have been mentioned so far. Table III summarizes the most fundamental of these. The design of both device types depends heavily on the wave height, length, and period. The designer must know what the wavelength of the longest wave to be utilized in an efficient manner should be 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 III
IMPORTANT DESIGN PARAMETERS FOR OWC AND POINT ABSORBERS

Oscillating water column	*Point absorber*
Wave height, length, and period	Wave height, length, and period
Chamber dimensions	Total mean water depth
By-pass valve control	Depth of device below water

B. Environmental impact

There are several environmental consequences to weigh before installing WECs. Each type of WEC poses different environmental risks as seen in Table IV. The main difficulttties involve the consequences to sea life and ship navigation [17]. 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.

C. Common research areas

Research into the field of WECs has led to 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. Table V gives an overview of addressed criteria, classified into OWC and PA type WECs, each with different subtopics of interest.

TABLE IV
ENVIRONMENTAL IMPACT OF WAVE ENERGY CONVERTERS
(X = POSSIBLE IMPACT, XX = MORE IMPACT THAN OTHER DEVICE)

Problem Area	*Impacts*	*PA*	*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

TABLE V
COMMON RESEARCH TOPICS ON OSCILLATING WATER COLUMN AND POINT ABSORVER TYPE OCEAN WAVE ENERGY CONVERTERS

Oscillating water column	*Point absorber*
Air pressure and flow control (bypass valve) Turbine designs Turbine control of wave energy absorption Hydrodynamic characteristics Overall design methods Moorings, installation, and foundation System resonance	Control techniques (maximum energy is captured if the device's motion is in resonance with the waves) Turbine design including new power take-off methods (hydraulic systems, linear generators, contact-less force transmission systems) Moorings, installation, and foundation

VI. Investigation of Future Research Topics

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. Hence, the power developed by any of the WECs 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 [14]. 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 [18].

Another area of interest is the hydrodynamic response of WECs 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 [19] with the conclusion that such simulations require significant computational effort.

Table VI summarizes other research topics needed in the field of wave energy according to our opinion.

TABLE VI
CLASSIFICATION OF FUTURE WAVE ENERGY RESEARCH TOPICS*

Mechanical	*Electrical*	*Other areas*
Hydrodynamic characteristics	Direct power take-off methods	Weather forecasting for real-time wave behavior
Indirect power take-off methods	Power conversion	Navigating around devices
Mech. reliability	Power controls	Standardized testing of devices
Long term fatigue of moorings, foundation, and anchorage	Power transmission	Cost effective waterproofing, corrosion resistant materials, offshore access
Mechanical maintenance	Electrical reliability	
Installation	Electrical maintenance	
	Grid connection requirements	

* Other than high-pressure underwater electric cables, purpose-designed inverters, and wave energy converter hydrodynamic response.

V. CONCLUSIONS

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 [1, 13].

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