Design of a Piezoelectric Energy Harvesting System for Shallow Ocean Waves

by

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Contents
Design of a Piezoelectric Energy Harvesting System for Shallow Ocean Waves .......... i
LIST OF TABLES ............................................................................................................. v
LIST OF FIGURES .......................................................................................................... vi
ACKNOWLEDGMENT .................................................................................................. vii
ABSTRACT .................................................................................................................... viii

1. INTRODUCTION / BACKGROUND ................................................................................ 1
   1.1. Why Shallow Ocean Waves are a Good Choice for Energy Extraction ...................... 1
   1.2. Shallow Waves and Near-Shore Considerations ............................................................ 5

2. THEORY / METHODOLOGY ............................................................................................. 8
   2.1. Shallow Wave and Energy Definition ........................................................................... 8
       2.1.1. Drag Force and Lift Forces on a Semi-submersible Body ..................................... 11
       2.1.2. Wave Shoaling and Wave Reflection ................................................................. 13
   2.2. Ocean Wave Energy Extraction and Ideal Damper Definition .................................... 13
   2.3. Piezoelectricity as an Energy Converter ................................................................. 16
       2.3.1. Piezo Stack Design Constraints ...................................................................... 21
   2.4. Design Considerations ............................................................................................. 23
       2.4.1. Environmental Impacts and Considerations for the Design .............................. 26
       2.4.2. Sustainability ..................................................................................................... 29
   2.5. Energy Storage and Transmission Considerations .................................................... 30
       2.5.1. Fly-Wheels ........................................................................................................... 31
       2.5.2. Ultra-Capacitors .............................................................................................. 33
       2.5.3. Batteries .............................................................................................................. 34
       2.5.4. Transmission Lines and Power Transmission to Shore ...................................... 34
   2.6. Using an Array of Devices .......................................................................................... 35
   2.7. Other Concerns – Legalities and Regulations ............................................................ 36

3. RESULTS / DISCUSSION ................................................................................................ 38
   3.1. Near-Shore Piezoelectric Converter .......................................................................... 38
   3.2. Comparison to Alternatives and Costs ..................................................................... 46

4. CONCLUSION .................................................................................................................. 53
   4.1. Conclusions ................................................................................................................. 53
4.2. Recommendations

4.2.1. Improvements

4.2.2. Considerations

4.2.3. Future Research

REFERENCES / BIBLIOGRAPHY

APPENDICES

1. List of Symbols

2. Definitions

3. Basic Wave Equations and Theory

4. Piezoelectric Energy Equations

5. Shallow Water Wave Data

6. Other References

6.1. List of wave energy converters

6.2. Selected Rubber Materials for Shallow Wave Device

6.3. Table of Sample Piezoelectric Materials and Properties
LIST OF TABLES

Table 1: Wave Resources by Region .......................................................... 2
Table 2: Wave Data – Sphere Damper ....................................................... 40
Table 3: Wave Data – Cylinder Damper .................................................... 41
Table 4: Wave Data – Sphere Damper, Radius Equal to Min Depth .......... 41
Table 5: Wave Data – Cylinder Damper, Height Equal to Twice Max. H_s ........................................................................ 42
Table 6: Wave Data – Sphere Damper, Min Radius for Acceptable F_D ................................................................. 43
Table 7: Wave Data – Cylinder Damper, Min Radius for Acceptable F_D ................................................................. 43
Table 8: Wave Data – Sphere Damper, Power Generation ......................... 44
Table 9: Wave Data – Cylinder Damper, Power Generation ......................... 44
Table 10: Wave Data – Sphere Damper, Total Power Generation and Efficiency ............................................................ 45
Table 11: Wave Data – Cylinder Damper, Total Power Generation and Efficiency ............................................................ 45
Table 12: Summary of Key Challenges and Priority Advances for Marine Renewables ............................................................ 47
Table 13: Wave Formulas ........................................................................ 69
Table 14: List of Wave Energy Converters ............................................. 73
Table 15: Selected Rubber Materials for Shallow Wave Device ................. 77
Table 16: Table of Sample Piezoelectric Materials and Properties ............... 78
LIST OF FIGURES

Figure 1: Wave Motion in Comparison to Depth\textsuperscript{1} ................................................................. 3
Figure 2: Shallow Water Waves\textsuperscript{2} .................................................................................................. 5
Figure 3: Buoyancy and Drag Forces on a Spherical Damper ........................................................................... 10
Figure 4: Upper Bounds of Absorbed Power of an Immersed Body\textsuperscript{16} ............................................. 15
Figure 5: Piezoelectric Disk Stack (Rod)\textsuperscript{36} .................................................................................... 18
Figure 6: Cylinder and Sphere Damper/Piezo-Rod ......................................................................................... 19
Figure 7: Forces on Piezoelectric Rod ............................................................................................................ 19
Figure 8: Tethered Buoyant Structures ............................................................................................................ 25
Figure 9: Fly-Wheel Configuration\textsuperscript{44} ................................................................................................. 31
Figure 10: Ultra-Capacitor\textsuperscript{43} .............................................................................................................. 33
Figure 11: Typical Off-Shore System-level Array Diagram, with the High Voltage DC Transmission Link\textsuperscript{25} ................................................................. 35
Figure 12: Proposed System Level Shallow Water Wave Energy Generation Array ........................................ 36
Figure 13: Probability Plot of Shallow Wave Power (1 year) ........................................................................... 39
Figure 14: Probability Plot of Shallow Wave Heights (1 year) ........................................................................... 39
Figure 15: Probability Plot of Shallow Wave Periods (1 year) ........................................................................... 40
Figure 16: Impact of the Marginal Cost of Pollution on Price\textsuperscript{24} .......................................................... 52
Figure 17: Modified Damper – Piezo model ......................................................................................................... 57
Figure 18: Wave Basics\textsuperscript{27} .................................................................................................................. 68
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ABSTRACT
Waves are an excellent source of energy, are a natural resource, and are renewable. Capturing wave energy in shallow water is an ideal solution for energy generation as a device can take advantage of wave energy at its maximum (potential and kinetic) points. How much energy is captured depends upon a number of factors: wave translation, wave height, the number of waves in a set period, the type of converter used and its efficiency of capturing both the potential and kinetic wave energy.

To maximize the amount of energy that can be extracted from a near-shore, shallow wave a simple method of converting the wave’s mechanical energy to an usable energy medium (i.e. electricity) is via piezoelectricity. This paper will touch upon fundamentals of efficient and economical extraction of energy from shallow ocean waves as well as discuss design considerations utilizing piezoelectricity as an energy converter. It can be shown that the capture and storage of shallow wave energy in this manner is comparable to energy generated from other sources, such as fossil fuels, solar power, and hydrodynamic.

Ocean waves generate terawatts of energy a year. Use of wave energy converters (WECs) is one way to capture this energy. Shallow ocean waves are particularly a good choice as not only are they closer to shore, reducing energy loss from transmission, but a designer can take advantage of the ocean floor and wave height increase to generate energy.

By evaluating incoming linear and non-linear shallow water waves using superposition, a model was built to evaluate resultant drag and buoyancy forces. These forces were then applied to determine an ideal damper volume for the given wave spectrum. By applying the two theories of optimum interference and Budal’s upper bound, an “ideal”, large and symmetrical damper volume of 2401 m$^3$ was calculated. Finally, an energy generator using piezoelectric material, PZT, was developed as a stack of disks (into a rod shape) to apply the drag force as a bending force and buoyant force as a tensile force on the piezo-rod, causing deflection and generating electricity.
Limitations in the manufacturing capabilities for piezoelectric materials and application of the shallow water, near shore data from the CDIP, placed constraints on sphere and cylinder damper models, ultimately requiring a decrease in spherical volume to $0.0011 \text{ m}^3$, a $10^5$ magnitude reduction, and the spherical volume ultimately winning out. With such a drastic reduction of absorbing volume, primarily due to the limits on bending stress for the stiff PZT material, a mean of $0.0189 \text{ W}$ per wave was generated from the (spherical) WEC in comparison to the input power of $454.88 \text{ W}$ per wave. By placing the device into an array (of 100 units) the power generated was able to be increased resulting in $1.89 \text{ W}$ to be generated per wave and roughly a total of $1.36 \text{ gigawatts}$ per year generated.

Other design consideration were evaluated including boundary conditions, various forms of WECs and their pros and cons, what an array system would look like and how it would function, and environmental impact of the ocean on material selection and sustainability. The preferred solution to shallow water, near shore model is to make a floating, tethered WEC that takes advantage of the 3 main degrees of freedom (Heave, Surge, Sway). This device must be also be adaptable to the changing ocean conditions and have minimal impact on the environment.

Regulations and impacts of cost on the lifecycle of the WEC as compared to fossil fuel and offshore WECs were also discussed and showed that there are additional pros and cons that can affect the overall cost for a WEC array system. It was found that though fossil fuel power plants are currently cheaper for energy costs, at 2-5 cents per kWh, than WECs, at 7 cents per kWh, as efficiency improves and research and development decreases the WEC costs are expected to drop into a competitive range. Additionally, as externalities are accounted for over the life of the WEC system we may see larger savings.

It was concluded that although a shallow wave system can be cost and energy efficient and produce some energy, the damper-piezo rod system modeled (in bending and tension) is an inefficient method in bending primarily when compared to conventional energy generation methods, such as coal and gas. It is recommended to further evaluate the design to not using bending forces, which are limited, and instead evaluate tensile force for piezo as it has a much
larger capability. Additionally, piezo materials with a larger electromechanical coupling factor, $K$, and lower stiffness should be evaluated. Finally, it is recommended that any model should be tested empirically.
1. INTRODUCTION / BACKGROUND

1.1. Why Shallow Ocean Waves are a Good Choice for Energy Extraction

Ocean waves are a naturally occurring phenomenon as well as a renewable energy source. Waves form in water when it is excited by external forces, such as wind, vibrations, displacement, etc. The primary reason why ocean waves are a good choice for energy extraction is that an ocean wave is an efficient carrier of energy. “The global power potential represented by waves that hit all coasts worldwide, has been estimated to be in the order of 1TW (1 terawatt = 10^12 W). Although this is only a small proportion of the world’s wind power potential, which, in turn, is only a small portion of global solar power, ocean waves represent an enormous source of renewable energy” (Falnes, 2007).

In the article Devices That Harness Wave Energy | Wave Energy Cost (Ocean Energy Council, Inc., 2009.), the author makes the following claims on why ocean waves are a good choice as an energy resource:

1. As waves can travel long distances with little energy loss, power prediction can be reliably estimated and produced from wave energy generation.
2. A small WEC should be able to produce 1000 times the kinetic energy as a larger wind device, due to the difference in transmission mediums; water being 850 times as dense as air.
3. Ocean waves are constant and more consistent, in comparison to wind and solar, resulting in higher overall input to a device.
4. Costs are generally lower as WECs are usually simpler, require less square footage, and need less infrastructure and support than wind devices.
5. WECs are small and quiet and have less environmental impact than comparative wind energy devices.

Wave energy increases with latitude and has greater potential on the west coast of the United States because global winds tend to move west to east across the Pacific Ocean.
Table 1 shows the gross wave energy resource by region. This is an estimate of the energy contained in the waves if it were converted to electricity.

<table>
<thead>
<tr>
<th>US Wave Resource Regions (&gt;10kW/m)</th>
<th>TWhours/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>New England and Mid-Atlantic States</td>
<td>100</td>
</tr>
<tr>
<td>Northern California, Oregon and Washington</td>
<td>440</td>
</tr>
<tr>
<td>Alaska (exclusive of waves from the Bering Sea)</td>
<td>1,250</td>
</tr>
<tr>
<td>Hawaii and Midway Islands</td>
<td>330</td>
</tr>
</tbody>
</table>

Wave energy is still largely undeveloped and could be argued to be an emerging market. If this market could be recognized and the terawatts of energy available capitalized upon, tremendous profit could be gained. The question is, though, how will this energy be extracted and integrated with the current and future energy grid? One way could be capturing the energy of shallow water waves via mechanical means.

This paper will focus on the visible waves that form in shallow water (as defined where the ratio of water depth, d, to wavelength, L, is < 1/20) as this is where the most mechanical energy can be harnessed. The energy per unit surface area in a wave is related to the square of the wave height. The wave speed and wave length decrease as the wave enters shallow water, therefore, due to conservation of energy, the energy per unit area of the wave has to increase, so the wave height and activity increases (as seen in Figure 1). This is known as wave shoaling. Cresting and breaking usually occurs when wave height = depth of water (Shoaling, 2010).
By capturing the energy of a wave while it is at maximum mechanical motion that energy can be most efficiently captured. This energy can be harnessed to be used in other forms. It can be applied to a selective apparatus to be translated into usable energy, in this case electricity.

“Exploiting the low, variable frequency motion of waves, and coupling the power to a fixed frequency and fixed voltage grid system, is a challenging task which device designers have tackled in different ways” (Nave, 2008)\textsuperscript{32}. One of the other benefits of shallow wave energy extraction over offshore is that it is closer to the power grid systems that such a system would feed into. This would result in reduced transmission energy losses.

From the article *Devices That Harness Wave Energy* | *Wave Energy Cost*\textsuperscript{10}, there are three basic methods for converting wave energy to electricity:

1. Float or buoy systems that use heave to drive generators. The WEC is either floating or moored to the ocean floor.
2. Oscillating water column devices that use wave surge and/or sway to force air through a column to turn a turbine. This device is usually shore mounted.
3. "Tapered channel" or "tapchan" system channels incoming waves into an elevated reservoir. The water then flows out of the reservoir due to gravity. Using standard hydropower technologies this flowing water is then turned into energy.

The three major types of energy converters can be further broken down and classified as it is useful for seeing the differences and similarities among various wave energy converters (WECs). From (Falnes, 2007)\textsuperscript{16}, WECs may be classified according to location (off-shore, near-shore or onshore; floating, submerged or bottom-standing), according to type of energy conversion machinery (mechanical, hydraulic, pneumatic or directly electrical), and according to type of energy for end use (electricity, water pumping, desalination of seawater, refrigeration, water heating, propulsion).

WECs may also be classified according to their horizontal extension and orientation. If the extension is very small compared to a typical wavelength, the WEC is called a point absorber. On the contrary, if the extension is comparable to or larger than a typical wavelength, the WEC is called a line absorber, but the terms attenuator and terminator are more frequently used. A line absorber is called an attenuator or a terminator if it is aligned parallel or normal to the prevailing direction of wave propagation, respectively. A list of various wave energy converters is located in APPENDIX 6.1. It can be observed that the majority of these applications are designed to operate in off-shore conditions and few have application for near-shore. “Devices such as the Salter duck are primarily geared toward large-scale power generation and would operate in deep seas. Devices being considered for small-medium-scale power generation would, however, tend to operate in shallower waters” (Korde, 1997)\textsuperscript{26}. This is because the majority of research on wave energy harvesting has focused on deep to mid-depth ocean waves where factors such as friction from the ocean floor, wave reflection, and effects due to the changing bottom can be ignored.

This thesis proposes that by capturing wave energy at maximum mechanical motion an optimized extraction of this energy can occur from shallow waves. Then by coupling
this energy extraction to a device (a WEC) that efficiently converts the mechanical motion into electricity, such as with piezoelectric materials, the energy that can be fed into a local power grid system becomes a comparable solution in comparison to conventional energy generation techniques for small to medium scale power generation. To perform this thesis, research of shallow wave energy background and theory was performed with specific interest in coastal applications and interaction with partially submerged surfaces. An analysis of an “ideal” shallow wave at near-shore will be reviewed and energy calculations generated. From these formulas, a device (ideal damper and converter/generator) will be conceived to extract the most amount of energy from the wave form with the intent to minimize loss and maximize the output of usable energy. This device should take into the environmental conditions and location, durability, and service life.

1.2. Shallow Waves and Near-Shore Considerations
When considering design and development of shallow water WECs a number of factors should be evaluated, starting with defining a shallow wave. From (Anthoni, 2000)\(^1\), waves lose energy, in particular in shallow water, mainly by wave breaking and by friction against the seabed; energy loss in the form of heat (as seen in Figure 2).

![Figure 2: Shallow Water Waves\(^1\)](image-url)
This is explained by Blenkinsopp. “Wave breaking is associated with the generation of high levels of turbulence, air entrainment, noise and splash, all of which must contribute to the energy dissipation and which are seen to increase with wave breaking intensity as waves become more plunging in nature. A relationship between breaking intensity and initial energy dissipation, showing that the total energy dissipated in the breaking event for each wave case increases as the relative cavity area becomes larger, i.e. as the intensity of breaking increases.” This is when the wave is at its highest point and right before it crashes over. Therefore a shallow wave WEC should be located before the locations where the wave will break (wave height = depth). Also, the gentler the slope of the beach, the more energy is retained. Steep slopes such as rocky shores do not break waves as much but reflect them back to sea. If the shore is rocky and steep sufficiently down into the water, then wave reflection may be more important than wave dissipation.

The variability of wave conditions in coastal waters is, generally, very large compared to offshore waters. Near-shore variation in the wave climate is compounded by shallow-water physical processes such as wave refraction, which may cause local “hot spots” of high energy due to wave focusing particularly at headlands and areas of low energy in bays due to defocusing. In addition, other coastal wave processes such as wave reflection, diffraction, bottom friction, and depth-induced breaking effects may have some influence. As such, it can be concluded that these influences will generally result in variation of expected energy inputs to a system or at most energy loss from ocean waves prior to extraction. These considerations should be evaluated when considering where to place a near-shore wave energy extraction device.

Korde notes that currently, the hydrodynamic design of most shallow-water devices appears to be based on linear theory, which assumes the wave amplitudes to be small. This is unlikely to be true during most of the operation of such devices, especially if these are to be placed in a region where focusing effects are noticeable or where storm surge occurs frequently. Furthermore, the effects of wave nonlinearity begin to be
important in any event as the water depth decreases. Korde advises that model testing be performed before theoretical performance analyses can be applied to the design of a shallow-water device. With these considerations in mind, an attempt is made in this work to analyze performance of a two-dimensional wave energy device operating in shallow-water waves.

There are additional considerations that one should explore when researching placement of a near-shore WEC. Maritime, structural, and electric state and federal regulations and guidelines, and environmental concerns and requirements all play a part in selection where and how a WEC may be used. Additionally, Fixed and Variable costs for the installation and maintenance over the life of the WEC will be a major driver into the profitability of such a device and understanding of whether it could compete with conventional energy generation methods. This will be discussed further in the Results (Chapter 3).
2. THEORY / METHODOLOGY

This chapter will explore the theories behind shallow waves and their energy, definition of an ideal damper for absorbing ocean wave energy, and piezoelectric materials and energy generation. These theories will be utilized to build a model/device that will ideally extract wave energy and use it to generate electricity from a piezoelectric generator.

2.1. Shallow Wave and Energy Definition

This chapter will focus on the wave energy definition for shallow waves. As a reference basic wave formulas may be referenced in APPENDIX 3.

In general shallow ocean waves are unsteady, irregular, and directional (El-Hawary, 2001) and will generally appear as several wave trains with different wavelengths and directions. This is because an ocean wave is composed of many elementary waves of different frequencies and directions (Falnes, 2007). This combination of waves can be viewed as an intermixing of both Regular waves, as defined in Linear Potential Wave Theory, and Irregular waves (Schamhart, 2005) and for a given period, \( T \), equal a resultant wave spectrum, \( \int_{0}^{2\pi/T} S(f)df \); in \( m^2/Hz \). The wave spectrum describes quantitatively how the different wave frequencies, \( f \), contribute to the wave energy.

This is also known as Superposition and can be evaluated by taking discrete statistical measurements of wave data to evaluate the wave spectrum. By taking advantage of the idea that all wave interactions on an object can be ultimately resolved into a single resultant, the unique 6 degrees of freedom found in the shallow wave system can be resolved; the most important being surge \( (X\text{-dir.}) \), sway \( (Y\text{-dir.}) \), and heave \( (Z\text{-dir.}) \). The shallow wave motions can be resolved from forces in \( X, Y, \) and \( Z \) into \( X' \) and \( Z' \) by applying the local resultant on a symmetric damper. This is important as it essentially changes a non-linear 3-D problem into a 2-D linear problem.
From (Falnes, 2007), the total per unit area of sea surface stored energy, \( E \), for shallow waves is defined as

\[
E = \frac{\rho g H_s^2}{8} = \frac{\rho g}{8} \int_0^{\infty} S(f) df
\]

(1)

where \( \rho = 1030 \text{ kg/m}^3 \) (mass density of sea water);
\( g = 9.81 \text{ m/s}^2 \) is the acceleration of gravity;
\( H_s \) is the significant wave height for the actual sea state.

\( E \) is equally partitioned between kinetic energy, due to the motion of the water, and potential energy, due to mechanical work performed when the flat water surface is being deformed to a wave. It should be noted that Eq. (1) should be evaluated as a summation over a finite number of wave frequencies. Also, for a sinusoidal wave with amplitude \( H/2 \), where \( H \) is the wave height (the vertical distance between crest and trough of the wave), \( H_s \) is equal to \( H\sqrt{2} \).

The unit surface area considered is a unit width times the wavelength, \( L \), so that the total energy per unit width is

\[
E_T = \frac{\rho g H^2 L}{8}.
\]

(2)

From (Khaligh, 2010), regular sinusoidal wave power, \( P_w \), can also be written as a function of wave height, \( H \), and period, \( T \), where

\[
P_w = \frac{\rho g^2 T H^2}{32\pi}
\]

(3)

To account for the irregular nature of waves in nature, the principles of superposition of irregular waves to measure the true non-linear wave power can be used. If the wave conditions are measured, over a known time, the \( H_s \) can be calculated. The significant
wave height is defined as the average of the highest 33% of the waves. Under such circumstances, the wave power level (energy/width of the wave front) can be stated as:

\[
P = 0.55H^2 T \text{ W/m.} \tag{4}
\]

It is very clear from the equation that the energy in waves is dependent directly on the wave height and period, which makes it a variable and intermittent source of energy (Jalihal, 2005)\textsuperscript{23}.

Now that the wave energy is defined it has to be extracted. Two ways to extract translational (X’) and vertical (Z’) energy are through the use of two forces, namely buoyancy and drag acting on a semi-submerged object (damper) (See Fig.3).

![Buoyancy and Drag Forces on a Spherical Damper](image)

**Figure 3: Buoyancy and Drag Forces on a Spherical Damper**

Buoyancy is historically defined by Archimedes Principle: *Any object, wholly or partly immersed in a fluid, is buoyed up by a force equal to the weight of the fluid displaced by the object.* This results from the fact that fluid pressure increases with depth and from the fact that the increased pressure is exerted in all directions (Pascal's principle) so that
there is an unbalanced upward (Lift) force on the bottom of a submerged object (Nave, 2008), as shown in Figure 3:

Drag, also called fluid resistance, is the force that resists the movement of a solid object through a fluid (a liquid or gas). The most familiar form of drag is made up of friction forces, which act parallel to the object's surface, plus pressure forces, which act in a direction perpendicular to the object's surface. For a damper resisting the ocean wave moving around it, the drag is the component of the net hydrodynamic force acting in the direction of the wave’s movement.

2.1.1. Drag Force and Lift Forces on a Semi-submersible Body

To make an approximation of the wave forces on a body (damper), which will be used to extract energy from a shallow wave, a linear model of the resultant forces on that body is used. Drag force and lift force occur on the body (El-Hawary, 2001). The drag force, \( F_D \), is the in-line force and the lift force, \( F_L \), is transverse force with regard to the fluid flow direction, which are expressed respectively as follows;

\[
\begin{aligned}
F_D &= \frac{1}{2} \rho \left( C_D \right) S_A \cdot v^2 \\
F_L &= \frac{1}{2} \rho \left( C_L \right) S_A \cdot v^2
\end{aligned}
\]  

(5)

where \( \rho \) is the fluid density, the drag coefficient \( C_D \) and lift coefficient \( C_L \) are functions of configuration of a structure and flow conditions, \( S_A \) is the projected area of a floating damper, and \( v \) is the relative velocity a shallow wave.

Practical values for \( C_D \) are 1.17 for a circular cylinder and 0.5 for a sphere. Practical values for \( C_L \) are 0.13 for a circular cylinder and 1.5 for a sphere.

To extract the most energy it is desired to have the highest \( F_D \) and \( F_L \) possible. Also, to take advantage of the resultant \( X' \) and \( Z' \) forces a symmetric body such as sphere or cylinder is necessary.
The $S_A$, projected areas, can be defined in the X’ and Z’ as follows:

\[
\begin{align*}
\text{Sphere} & \quad \begin{bmatrix} X' \\ Z' \end{bmatrix} = \begin{bmatrix} \frac{\pi r^2}{2} \\ \frac{\pi r^2}{2} \end{bmatrix} \\
\text{Cylinder} & \quad \begin{bmatrix} X' \\ Z' \end{bmatrix} = \begin{bmatrix} \frac{\text{width} \times \text{height}}{2} \\ \frac{\pi r^2}{2} \end{bmatrix}
\end{align*}
\]

For a half-submerged volume with an equivalent radius ($r$), where width = 2$r$ and height = 2$r$, the cylinder has the larger projected area in X’ direction than a sphere and higher $C_D$ and would result in a higher $F_D$ than a sphere. As the $S_A$ projection in the Z’ direction is the same for each volume and $C_L$ is greater for a sphere than the cylinder, the sphere results in a higher $F_L$ than a cylinder.

The relative velocity of the wave, $v$, has X’ and Z’ components $\begin{bmatrix} u \\ w \end{bmatrix}$ given by

\[
\begin{align*}
u &= \frac{H}{2} \sqrt{\frac{g}{d}} \cos \theta \\
w &= \frac{H \pi}{T} \left(1 + \frac{z}{d}\right) \sin \theta
\end{align*}
\]

(6, 7)

Where $z = -d$, $\theta$ = wave phase in radians (see APPENDIX 3).

By substituting equations (6) and (7) back into Eq. (5) and using the typical values of all parameters the maximum forces that a wave will generate on a semi-submerged object can then calculated. This will be shown in the Results, Chapter 3.

Through a free body diagram and applying the conservation of energy, the relation of the vertical and horizontal forces between the wave and a partially submerged object can be defined. As a result, an object that resists both the translation of the wave and vertical movement of the wave would transfer a portion of this energy through an apparatus where it could be transformed.
2.1.2. Wave Shoaling and Wave Reflection

From (Shoaling, 2010)\textsuperscript{42} waves entering shallow water increase in height and conserve period and, with the exception of minor losses, up to breaking, conserve energy. However, wave celerity decreases as a function of depth and correspondingly wavelength shortens. Additionally assumptions should be taken for a known celerity, \( C \), for a known coastline and known period, \( T \), and that shoaling has already occurred prior to reaching a wave energy extraction device and has been accounted for locally at the location of the device.

Wave reflection (reflected energy) can occur when the shore incline is sufficiently steep and/or rocky. This can be mitigated by proper selection of shore incline to be gradual. As a recommendation shore lines should be tested and evaluated for reflection prior to placing a device. This will not be covered in this paper.

Additional wave reflection can come from the interaction of waves between floating objects as part of the wave can reflect and interact with one or more neighboring energy extraction devices. This can be mitigated when placing devices close to neighboring objects and ensure adequate spacing to limit the amount of reflected energy. Alternatively, if a damper device is design with reflection in mind, this energy can be captured as an additional input.

2.2. Ocean Wave Energy Extraction and Ideal Damper Definition

This chapter will focus on the extraction of energy from an ocean wave by using an ideal damper.

A floating structure free to move in water will experience six degrees of motion (surge, sway, heave, pitch, roll, and yaw). For a symmetric moored structure only three motions are important – surge, sway, and heave (Chakrabarti, 1984)\textsuperscript{8}. It should be noted that surge, heave, and sway displacements are not generally in phase with one another.
To extract the maximum amount of energy from a wave the conservation of energy requires that devices interacting with a wave should decrease its energy. An optimal device should generate a wave which interferes destructively with the ocean wave. “In order for an oscillating system to be a good wave absorber it should be a good wave generator” (Falnes, 2007).

Wave energy consists of potential and kinetic energy that results from the vertical (Z - heave) and horizontal (X – surge, Y- sway) translations. By designing an ideal damper apparatus that would utilize both the vertical and horizontal energy, the maximum amount of wave energy possible could also be absorbed.

When considering heave, it should be considered as an advantage that practically all the volume, of e.g. a heaving-float system, could be “used to displace fluid and thus to generate outgoing waves”. Falnes advocates that an economic wave-energy converter should have a large working area (wave-oscillator interface) relative to its size, and that this area should have a relatively large oscillating speed. Secondly, he indicates that the working area should preferably be resonant or “quasi-resonant”. Corresponding to optimum wave interference, there is an upper limit, $P$, to the amount of absorbed wave power (energy) that can be extracted from a deep ocean wave by means of a particular oscillating system, $P_A$.

$$ P < P_A \equiv c_o T^\delta H^2 $$

where $c_o = \alpha \rho (g / \pi)^{\frac{5}{12}} = 245 \text{Wm}^{-2} \text{s}^{-3}$,

$$ \alpha = \begin{cases} 2 & \text{vertical wall} \\ 1.33 & \text{assumed value for gradual 30° beach} \\ 1 & \text{open flat sea} \end{cases} $$

$\delta = 1 \text{ (optimal destructive wave interference)}$,

and $T$ is the wave period. According to inequality Eq. (8), the values of absorbed power and converted useful power are bound to the region below the increasing curve in Fig. 4.
Falnes\textsuperscript{16} also references another limit exists known as Budal’s upper bound, $P_B$, which is the ratio of extracted energy to the volume of the immersed oscillating system as defined by:

$$P < P_B \equiv c_0 V H / T$$  \hspace{1cm} (9)

where the wave height $H = 2A_0$, where $c_0 = \alpha \pi \rho g / 4 = \alpha 7.9 kW / m^3/s$, with where $V$ is the volume of the heaving body, and $A_0$ is the elevation amplitude of the incident wave. Falnes warns that unless the a damper is designed for optimum wave interference’s upper limit and Budal’s upper bound the performance of a WEC may typically correspond to figures that are one to two orders of magnitude below Budal’s upper bound.

These two formulas help us set limits to the wave energy absorber design volume based around anticipated wave $T$ and $H$ for a known location for heave (see Fig. 4).

![Figure 4: Upper Bounds of Absorbed Power of an Immersed Body\textsuperscript{16}](image)

By assuming that max energy absorption occurs when $P_A = P_B$, and equating (8) and (9) together and then solving for $V$ (for $\alpha = 1.33$) volume yields
\[ V = 31.01HT^2 \]  \hspace{1cm} (10)

Next compare the symmetric volumes from Chapter 2.1.1:

\[
\begin{align*}
\text{Sphere} & : \quad V = \frac{4}{3} \pi (R^3 - r^3) \\
\text{Cylinder} & : \quad V = \pi h (R^2 - r^2)
\end{align*}
\]

Comparison of symmetrical volumes of radius \( r_{\text{outer}} \) and having a rod with radius \( r_{\text{inner}} \) in the middle and equating radius \( r_{\text{inner}} \) to zero, setting \( h = 2R \), a cylinder has the larger volume and would absorb the most energy for a given system. But the half immersed sphere does not experience any pitch moment about an axis through its center since all pressure forces acting on its surface are directed through the center (Mercier, 1971\(^{28}\)). These considerations will be evaluated further and selection of the damper body will be made in the Results, Chapter 3.

### 2.3. Piezoelectricity as an Energy Converter

This chapter will discuss using piezoelectricity as a high efficiency energy converter. It should next be considered how to transfer the absorbed mechanical wave energy through a medium or device to generate electricity. This could happen in a number of ways. Machines such as pistons, generators, flywheels, and piezoelectric have been used in a variety of functions in this way and would be ideal for generating electricity from mechanical energy.

From *Piezoelectric Energy Harvesting: Modeling and Application* by Inman\(^{22}\), piezoelectricity results from a class of ceramics and crystals that exhibit the piezoelectric effect. When the material is mechanically strained, electric polarization proportional to the applied strain occurs resulting in an electric charge/voltage. This is a reversible effect and the opposite happens when electricity is applied the material; the material deflects.
Piezoelectric materials are a great choice for energy conversion as they are one of the only materials that directly convert mechanical energy to electricity with minimal loss; for example lead zirconate titanate (PZT) is able to convert 80% of the mechanical energy applied to it into electrical energy (Wojciechowski, 2010). Additionally, the material (made of either crystal or ceramics) is simple having only the crystal itself and a pair of connection leads make up a device.

The piezoelectric device used in the shallow wave application as envisioned would operate in both tension and first mode bending. It should be noted too, as piezoelectric materials are considered brittle and the piezo-device should be designed to stay within the elastic limit. The piezo-rod should be shaped as a cylinder to keep aligned with the symmetric concept discussed above in Chapter 2.1. As the ocean is much larger than the rod, it can be considered as a large heat sink and therefore that there is minimal thermal strain in the rod. To aid in calculations it can also be assumed that the piezo-cylinder is homogenous, anisotropic and poled in the $Z'$ direction, designed to not operate in the natural frequency of the piezoelectric rod.

For a damper/piezo-generator application, piezoelectric crystals and ceramics are commonly manufactured today. They can come in many forms for various applications. In this case, a manufacturer would manufacture crystal or ceramic rods, if they could be long enough to be practical or stack piezo-disks (see Fig. 5), into a rod shape using a binding agent. To protect the disks and act as a binding agent a designer could encase the rod in biocompatible rubber, similar to how Wojciechowski proposes. The rubber would also act as a resistor, protecting the current flowing from deformed disks via electrodes and to attached transmission wires from disrupting if sea water were to interact. These wires could be attached to the rod ends to create a circuit and the output transmitted to a storage device or input into an electronic grid.
For this paper it will be assumed that the thickness of the beam is small in comparison to the length, so that the effects of shear deformation and rotary inertia of the beam can be neglected. It will also be assumed that all bending is symmetric with respect to the centerline. Additionally, it will be assumed that a uniform strain model where a through-the-thickness variation of strain in the active piezo-device is uniform and that no strain results from the infinitely thin bonding layer between piezo-disks\textsuperscript{20}.

The proposed WEC shallow wave system(s) now resemble a “ball on a stick” damper/piezo-rod set-up as shown in Figure 6
Figure 6: Cylinder and Sphere Damper/Piezo-Rod

The incoming wave motion acts upon the damper causing lift (tension) and drag (bending) forces (as shown in Fig. 3 and in Fig. 7) upon the piezo rod as the wave goes through its phases (see APPENDIX 3).

Figure 7: Forces on Piezoelectric Rod

Where $dL = SWL = \text{midpoint of damper} = \text{depth (d)}$
To determine the amount of Power, \( PP \), per unit volume that the piezo device would output, for efficiency comparison to the input wave power, the amount of voltage and current generated from the displacement of the disk stack should be determined, where

\[
PP = V_0 \times i
\]

where \( V_0 \) = voltage (Volts) and \( i \) = current (amps).

PP can also be determined mechanically as shown in (Khaligh, Onar, 2010)\(^{25}\) and (Zurkinden, Campanile, Martinelli, 2007)\(^{51}\), where the power output (\( PX', PZ' \)) per unit volume of a stack of piezo disks would be

\[
\frac{PX'}{V} = \frac{\pi d_{31}^2 s^2 Y_m^2 f}{2\varepsilon_0} \quad (11a)
\]

\[
\frac{PZ'}{V} = \frac{\pi d_{33}^2 s^2 Y_m^2 f}{2\varepsilon_0} \quad (11b)
\]

where:

\( d_{31} \) and \( d_{33} \) are the mechanical-to-electrical coupling parameters; \( s \) is the strain \( Y_m \) is the modulus of elasticity of PZT (63 GPa); \( f \) is the frequency; and \( \varepsilon_0 \) is the material’s dielectric constant / permittivity, and \( V \) is the volume of the strained portion of the rod.

By using the definition of the electromechanical coupling efficiency\(^{25}\), \( k \), where

\[
k_{31}^2 = \frac{d_{31}^2 Y_m}{\varepsilon_0}, \quad k_{33}^2 = \frac{d_{33}^2 Y_m}{\varepsilon_0},
\]

and knowing that \( f = 1/T \), can substitute back into equations 11a and 11b to get

\[
\frac{PX'}{V} = \frac{\pi s^2 Y_m k_{31}^2}{2T} \quad (11c)
\]

\[
\frac{PX'}{V} = \frac{\pi s^2 Y_m k_{33}^2}{2T} \quad (11d)
\]
The elastic stress and strain limits of the device should next be considered to keep it from deforming plastically and cracking due to brittleness. This could limit the size of a damper and the amount of energy that can safely be extracted from the piezo rod/stack generator.

To understand the limits of the piezoelectric stack (rod) calculate the max allowable stress, shear, and deflection for the chosen material type and assuming that $F_D$ and $F_L$ had no losses when coupled from the damper to the piezo-rod.

**Stress:**

\[
\sigma_x = \frac{F_D L}{0.78r^3}; \text{ max bending stress in X' direction} \quad (12)
\]

\[
\sigma_x = \frac{F_L - mg}{A}; \text{ max stress in Z' direction.} \quad (13)
\]

where $r =$ radius of the rod, $L$ is the length of the rod, $A$ is the area of the rod.

**Strain:**

\[
s_{x'} = \frac{Mr}{EI} = \frac{F_D (dL)r}{EI} \quad (14)
\]

\[
s_{z'} = \frac{\sigma_{z'}}{E} \quad (15)
\]

where $I = 0.78r^4$, and $E$ is the modulus of Elasticity, and $M$ is the moment.

### 2.3.1. Piezo Stack Design Constraints

An ideal design would want the rod to be as long as the maximum shallow water depth that the system would observe. This may not be practical though due to current manufacturing constraints. Additionally, as mentioned above one would want to choose a piezo crystal or ceramic that is both tough and has a high $K$ for both tension and bending on the stack. For the purposes of this thesis PZT was selected as a material that meets these requirements. Information on some piezo materials is in APPENDIX 6.3. Now that a material is selected the limits that are imposed on the system should be evaluated.
Some current limits on commercial manufacturing and use of piezo stacks are as follows$^{20, 34, 37}$.

- Most high-voltage actuators consist of ceramic layers measuring 0.4 to 1 mm in thickness, $t$. Choosing the largest thickness, 1mm, and assuming the bonding agent is very small compared to the disk thickness, the rod would require approximately 3320 piezo disks for the max $d = L = 3.32$ meters.

- Commonly manufactured piezo stacks can achieve a relative safe displacement of up to 0.2 % and can be built with disk aspect ratios up to 12:1 (length:diameter). Which means for the thickness, $t$, equal to 1mm the diameter could at most equal 12 mm (0.47 in.) making the disk area, $A = 113.1$ mm$^2$ ($0.00011$ m$^2$, $0.001$ ft$^2$). and each disk’s volume equals $1.1 \times 10^{-7}$ m$^3$ (mass of each disk is 0.00089 kg, mass of the stack is 2.94 kg).

- To maintain the high efficiency of the piezo device it is recommended to evaluate stress and strain limits to ensure it is operated in the elastic range. If an over-load is applied the material will become damaged. Additionally, the stack should not act in compression as it is much weaker than when in tension.

- PZT ceramic material has yield strength up to 250 MPa ($250 \times 10^6$ N/m$^2$). This value should not be used in practical applications, however, because depolarization occurs at pressures on the order of 20% to 30% of the mechanical limit, which is roughly 50 - 75 MPa ($50 - 75 \times 10^6$ N/m$^2$; 1N = 1kg*m/s$^2$). For an upper limit it will be assumed that the maximum allowable stress is 75 MPa.

Applying the piezo design constraints to equations (12) – (15), the following results:

**Stress:**
max $F_D$ for bending stress in $X'$ direction = 3.8 N ($3.8$ kg*m/s$^2$)
max $F_L$ for tensile stress in $Z'$ direction = 8250 N ($8250$ kg*m/s$^2$)

**Strain:**
max allowable bending strain, for all 3320 disks, using max $F_D$, $s_{x'} = 0.0012$
max allowable tensile strain, for all 3320 disks, using max $F_L$, $s_{z'} = 0.00043$
By applying the max allowable deflections and limits for PZT back into equations (11c, 11d) for the X’ and Z’ directions the max generated power in Watts for the device results in:

\[
P_{X'} = \frac{\pi \left( \frac{F_p (dL)}{EI} * (d + \frac{H}{2} \cos \theta) \right)^2}{2T} Y_m k_{31}^2 * (d + \frac{H}{2} \cos \theta) * A
\]

\[
P_{Z'} = \frac{\pi \left( \frac{F_p - mg}{AE} * (d) \right)^2}{2T} Y_m k_{33}^2 * (d + \frac{H}{2} \cos \theta) * A
\]

(16) \hspace{1cm} (17)

Equations (16) and (17) assume that the only piezo disks that will generate energy are those that are strained, which are a function of the water depth, d, and the wave height, H. Application of equations (16) and (17) with applicable limits and model inputs will be evaluated further in Chapter 3.

**2.4. Design Considerations**

This chapter will focus on other design considerations for a piezo/damper device and considerations for performing necessary calculations. Topics will be identifying necessary boundary conditions, exploration on WEC types and how to moor a device, and discussion on environmental and regulatory considerations.

The calculations and assumptions in chapter 2.1-2.3 for the shallow wave energy extraction device would have the following boundary conditions:

1. Water does not penetrate the damper or converter or the free surface.
2. At the free surface there is atmospheric pressure.
3. Far away from the device, the flow is undisturbed.
4. Waves generated by the device radiate away from the device and are not reflected at the artificial boundary of the domain.
5. Forces (and moments) not in equilibrium result in device motions.
6. At the bottom (z = -d),
No slip:  \( u = v = 0 \)

No normal flow:  \( u \frac{\partial d}{\partial x} + v \frac{\partial d}{\partial y} + w = 0 \)

Bottom shear stress:  \( \tau_{dx} = \tau_{xx} \frac{\partial d}{\partial x} + \tau_{xy} \frac{\partial d}{\partial y} + \tau_{xz} \)

** Where \( \tau_{dx} \) is specified bottom friction (similarly for y direction).

9. At the free surface (\( z = \eta \)):

No relative normal flow  \( \frac{\partial \eta}{\partial t} + u \frac{\partial \eta}{\partial x} + v \frac{\partial \eta}{\partial y} - w = 0 \)

\( \eta \) is the elevation of the free surface relative to the Still Water Line (SWL).

\( p = 0 \), Surface shear stress:  \( \tau_{xx} = -\tau_{xx} \frac{\partial \eta}{\partial x} - \tau_{xy} \frac{\partial \eta}{\partial y} + \tau_{xz} \)

** Where the surface stress (e.g. wind) \( \sigma_x \) is specified (similarly for y direction).

10. The boundaries of the solution domain are solid walls where no-slip boundary conditions are applied. The no-slip condition ensures that the fluid moving over a solid surface does not have velocity relative to the surface at the point of contact. For the floating damper, the no-slip condition also means that the vertical heave velocity is imposed on the water particles at the boundary of the damper.

In interfacing with the waves, any damper/converter must be constricted so that wave forces are resisted. Ways of constraining a damper/converter for shallow water applications are:

1. Using the sea-bed for fixing or mooring – this has the benefit of ensuring the device does not move from the desired locations and allows a designer to take advantage of all six degrees of freedom (as seen Figure 8 examples). In addition, in a near shore, shallow water area the device could be designed to move with the tide if a tether is used. The biggest disadvantages are if using a tether of a fixed length the device can move somewhat arbitrarily from the waves’ interaction with it resulting in a loss of energy conversion and if the seabed changes drastically around a fixed device, it could become un-optimized.
2. Mounting several converters on a common frame or spine so that relative motion is obtained between them - this has the advantage of combining efforts from multiple devices for each wave. The biggest disadvantage is directionality of the frame to incoming waves. APPENDIX 6.1 references these types of converters.

3. Using the inertial force due to the gyroscopic action of a flywheel – this has the advantage of utilizing the cyclical nature of waves to apply / maintain force. But this could be affected by tidal change for a fixed device and typically only applies to 3-degrees of freedom (pitch, yaw, and roll). APPENDIX 6.1 references these types of converters.

4. Relying on the mass and inertia of the device – this uses the mass of the device as resistance against the motion of the incoming waves to convert energy but will only work in the primary 3-degrees of freedom that it is designed to capture (surge, sway, heave). APPENDIX 6.1 references these types of converters.

Figure 8: Tethered Buoyant Structures
Another design consideration that should be considered is tuning a damper to take advantage of resonance\(^2\). By tuning for resonance you can achieve maximum destructive interference with a wave. The difficulty with this though is that the ocean is comprised of a very broad wave spectrum. Only by modifying the absorber geometry can one effectively tune for each target spectrum\(^{15}\). As this is difficult to design and can be costly it is advised to design the absorber to tune to the mean wave energy.

As the expected wave height could exceed parameters due to storm surge, seismic activities, etc. it is advisable to build in a release between the damper and generator that would separate the two when wave forces upon the damper exceed acceptable limits. The floating damper could stay attached to the mechanism by means of a cord or rope so that the damper is not lost and could be later reattached.

\[ \text{2.4.1. Environmental Impacts and Considerations for the Design} \]

Wave power structures that are properly designed with both the environment in mind and for longevity can minimize environmental effects. “Properly engineered wave power is renewable, green, pollution-free, and can be environmentally invisible” (Devices, 2009)\(^{10}\).

There are a number of environmental issues and concerns that should be addressed when planning and designing shallow water WECs. As mentioned above in Ch.1.2, shallow water waves that are moving toward shore eventually break and also slow down due to friction against the seabed. The breaking causes turbulence. This dissipation of energy against the seabed causes constant changes in the way the sea floor is shaped; including its smoothness, pitch, etc. by transporting sand from deeper down towards the shore and by washing the sand and removing fine particles. Waves stir and suspend the sand so that currents or gravity can transport it (Anthoni, 2000)\(^1\).

Additionally, sea water itself being very salty is corrosive to materials. Corrosion is caused by the electrochemical reaction in which a metal anode corrodes by oxidation and
a cathode undergoes reduction reaction. Seawater works as an electrolyte for the transfer of ions and electrons between the two electrodes (Taylor&Francis, 2006)\(^7\). The rate of corrosion should be a factor considered in any design when choosing materials for the device.

To measure environmental impact of a proposed WEC, a study should be performed. (Wilson, 2008)\(^{49}\) proposes that the WEC might affect many aquatic species. Environmentalists and commercial fishermen are concerned with marine entanglement, whale and fish migration and the effects of electromagnetic fields (which are generated by the wave energy buoys) on electro-sensitive species like sharks, rays and salmon. (Anthoni, 2000)\(^1\) confirms this when he suggests that in shallow water, from surface to greater than 30m a large biodiversity exists that depend upon the waves for their survival.

One recommendation to minimize the impact of WECs to is to minimize the size of the system installed. (Pelc, Fujita, 2002)\(^{35}\) argue that, “covering very large areas of the surface of the ocean with wave energy devices would potentially harm marine life and could have more widespread effects, by altering the way the ocean interacts with the atmosphere”.

WECs, like wave breakers, calm the sea. But this could adversely impact marine life and fisheries by altering the natural mixing of water and earth that is produced by the waves. This would effectively change the local environment, especially on the surface where fish species depend on the waves for their spawning and feeding grounds.

Pelc and Fujita go on to comment though that there are potential benefits of a WEC system. There could be a dampening effect that would reduce erosion and the local impact of damaging storm waves, depending upon the type of shore the system is placed in. Additionally, the system could act as a type of artificial reef and could enhance marine life locally.
As part of the WEC, study sound propagation underwater must be considered as too much sound can be disruptive to the local ecology. “Studies have shown that sound propagation through water from WECs may not affect sea life as long as creatures in that area are used to the sound of passing motorboats, which emit a similar sound” (Taylor & Francis, 2006).

One benefit of shallow, near-shore WECs over off-shore is that off-shore WECs can often interfere with shipping routes or large pleasure craft as well as lie in the way of fishing areas or even migrating/mating whale habitats. The underground cable that provides energy to shore may also interfere with fishing areas. A near shore WEC does not have these problems, though it will be more visible to those on the shore potentially causing a political rather than an environmental one.

To withstand this difficult environment marine-grade materials and coatings should be selected to protect equipment from the corrosive environment. A good starting place would be to emulate other design concepts. For example, protection for offshore wind turbines in highly corrosive marine environments is defined in the EN-ISO-12944 standard, which requires the must last over its design life of 20 to 25 yr. by using coatings and other resistant materials (Taylor & Francis, 2006).

In the case of a damper/generator system a designer should ensure that the components would survive a similar life. The floating damper would need to stay buoyant, be tough, and still absorb energy. Marine grade foams, plastics, and rubbers such as such as Ethenepropenediene (preferred), Nitrile Ribber, Butadiene, Strenebutadiene, or Natural are very close to the density of salt water and have high energy resistivity (see APPENDIX 6.2, Table 5) in addition to being resistant to corrosion. Or a buoyant marine foam could be coated. A typical coating system used on onshore wind turbines, consists of 50 to 80 μm epoxy-zinc-rich primer, 100 to 150 μm epoxy mid-coat, and 50 to 80 μm polyurethane topcoat (Taylor & Francis, 2006) to provide protection. To
minimize impact on local aquatic life it is also recommended to make the absorber translucent or transparent, to minimize the effect of the device. For the piezoelectric rod/stack, this could also by encase in the above protective rubbers, as discussed in (Wojciechowski, 2010)\(^{14}\). This would effectively protect not only the piezoelectric material but also any wires and electrodes used in the system. Other mechanical parts are recommended to be galvanized metals. The mooring of the device should be concrete or metal protected against the not only the salt water but also against abrasion from sand or rock and the intrusion of marine life, such as barnacles.

The placement of a moored system in the shallow water along the coastline must be evaluated for minimal impact. WEC structures can alter many physical properties of the shore to often induce undesired effects. As (Meadows, Woods, 2003)\(^{27}\) advises “these alterations of natural processes can take the form of increased reflectivity to incident waves, interruption of long-shore currents and resulting long-shore sediment transport, alteration of incident wave patterns and the generation of abnormal underwater topography.” This changing of the topography could result in not only environmental impact but also in changing the wave energy spectrum and could effectively “de-tune” the proposed ideal damper solution and result in potentially less energy absorption. The designer should consult the appropriate ocean engineering handbooks for how to place structures along a coastline for minimal impact to the topography.

### 2.4.2. Sustainability

Sustainability of the shallow water device is both a combination of selection of materials (as discussed in 2.4.1) and maintenance/inspection. By performing regular maintenance and inspection it is expected that the device will work longer and costs will be reduced. (Wojciechowski, 2010)\(^{14}\) makes mention that though no federal regulations exist in regard to inspecting the equipment in ocean devices the Naval Facilities Engineering Center outlines procedures for maintaining and inspecting structures based on good engineering practices in their Underwater Inspection Criteria. The manual makes recommendations that devices should be built to operate for 20 yr. with minimal
maintenance and inspections of the device should be conducted periodically during its lifetime to search for apparent physical signs of deterioration, damage, corrosion, deterioration, and fatigue stress.

A damper, piezo-generator system, like the one proposed above, would have fewer (moving) parts and would, if designed properly, break less. Additionally, systems such as the safety release mechanism mentioned above, would help to keep the system from being damaged.

2.5. Energy Storage and Transmission Considerations
This chapter will focus on the how energy generated should be stored and/or transmitted to a local grid. As shallow water ocean waves have a large variation of wave energy input, (Falnes, 2007)\textsuperscript{16} recommends that short-time ($10^2$s) energy storage that has the ability to rapidly store variation in input and transmit voltage be used. To do this efficiently it is recommended to look at devices such as fly-wheels, ultra capacitors, and batteries. This chapter will also address transmission of energy and the benefits of being near to the shore as well as show what a proposed array system of shallow water WEC devices would look like.
2.5.1. Fly-Wheels
Large metallic flywheels have long been used in many applications for both storing and smoothing energy. They do this by accelerating a rotor up to a high rate of speed and maintaining the energy in the system as kinetic energy and then release its energy by reversing the charging process and slowing down (Fig. 9).

![Fly-Wheel Configuration](image)

This process can be repeated many times, very quickly without any damage to the unit because the energy is stored mechanically, not chemically. Thus nearly an infinite number of cycles, over a 20-25 year life of the device, can be obtained. As improved power electronics, vacuum housings, and magnetic bearings become more widespread, round-trip efficiencies of flywheel systems have improved and many current production models are in the 70% to 80% range, with some of the new designs even higher.

Renewable energy sources, like ocean waves, suffer from intermittency that can be reduced through the use of flywheels. Through incorporating a flywheel-based energy
storage unit into a shallow wave device, three problems can be addressed: to stabilize the frequency variations stemming from the device, to capture excess energy from short-term peak waves and to eliminate the need for spinning/standby generator reserve.

A flywheel can be used to regulate frequency and voltage sags, such as would be observed from the changing power input of ocean waves (i.e. the wave spectrum). Fluctuations in the energy obtained from the variable amount of power from each individual wave could wreak havoc on the power grid if coupled directly. Flywheels can instantly absorb power when demand drops and deliver power when demand rises, allowing the distributed generation device to catch up with the load a few seconds later, thereby matching the needs of the grid providing steady energy to meet the demand.
2.5.2. Ultra-Capacitors

Ultra-capacitors offer the capability of providing high power and lower energy storage that can charge and discharge very quickly, and are able to go through a large number of cycles without degradation\textsuperscript{43}. This is because, unlike a battery which uses chemical reactions to absorb and discharge energy, there is no chemical reaction. Instead, the energy is stored as a charge or concentration of electrons on the surface of a material. The energy can be released in a microsecond, much faster than from a chemical reaction. An ultra-capacitor, also known as a double-layer capacitor can be viewed as two non-reactive porous plates, or electrodes, immersed in an electrolyte, (Fig.10), with a voltage potential applied across the collectors. Once the ultra-capacitor is charged and energy stored, a load can use this energy.

Ultra capacitors also have the following additional benefits: They do not release any thermal heat during discharge; have no danger of overcharging and are not affected by deep discharges as are chemical batteries; have a long lifetime estimated to be 20 years; have approximately DC-DC round-trip efficiency of 80\%-95\% in most applications;
have an operating temperature range between -50°C and 85°C, and do not release any hazardous substances that can damage the environment.

Similar to fly-wheels, these characteristics make ultra-capacitors very useful devices for energy storage in shallow wave applications where they can instantly absorb power when demand drops and deliver power when demand rises, allowing the distributed generation device to catch up with the load a few seconds later, thereby matching the needs of the grid providing steady energy to meet the demand.

### 2.5.3. Batteries

As discussed above fly-wheels and ultra-capacitors are well suited to replace batteries in many applications as they, like batteries, can be scaled to meet the needs of specific applications. Because batteries take time to charge and discharge due to the chemical reactions involved they are not well suited to meeting both the power variation and frequency spectrum of near shore wave applications. The chemical reactions also have parasitic thermal release that causes the battery to heat up, slow damaging the battery resulting in a limited life cycle with a degrading performance. Finally the acids used in batteries are hazardous to the environment. The benefits though that a bank of batteries could provide to a grid though are large amounts of steady power and batteries are usually cheaper. A better application of a battery pack could be coupling with a fly-wheel and/or ultra-capacitor as a means to increase efficiency of power flow into the grid. This will be explored further in Chapter 3.

### 2.5.4. Transmission Lines and Power Transmission to Shore

Offshore energy generated by wind farms and deep ocean wave generators are transmitted to the shore by cables running under water. As the generators produce low voltage (around 690V A/C), an electrical substation next to the device(s) is required to step up voltage (to the kV A/C range) to ensure transmission and results in some energy loss. Costs for the farms and devices increase because of the capital costs for these substations (an above water platform, steel building, step-up transformer, switchgear,
emergency diesel generator, controls and instrumentation, staff and service facilities, helipad, crane, and a boat) as well as the capital costs required for laying cable to a shore facility for tie-in to the grid (costs of a primary, and where able secondary cable, burial of the cable 1 to 12 m deep in offshore ground to protect it from ship anchors and sea currents, inspection and maintenance).

Shallow water, near shore systems do not have all these increased costs or energy losses. Transmission lines run much shorter and therefore do not have to be stepped up to the kV level of offshore systems, resulting in lower costs and less energy loss. Transformers and energy storage devices can be located in the same location as tie-in to the grid, thereby lowering overall capital costs. Maintenance does not need to take into account working in deep water as a concern either. This is discussed further in Ch.3 Results.

2.6. Using an Array of Devices
A sea-bed moored point absorber can efficiently absorb energy from an ocean wave, but will be limited to only absorbing the portion of a wave that is interfered with by the damper. To increase energy absorption it has been recommended to utilize an array of point absorbers⁴¹. As seen in Figure 11, a typical set-up for Off-Shore Arrays would consist of an array of absorbers that power energy generators (A/C).

![Figure 11: Typical Off-Shore System-level Array Diagram, with the High Voltage DC Transmission Link]
The A/C output is changed to D/C, boosted and transmitted long distances via cable to be changed back to A/C and integrated into the grid via a transformer. A shallow wave set-up does not need to do this.

By spacing shallow water moored point absorbers in an array format benefits can be anticipated (see Fig. 12) in addition to those mentioned in Chapter 2.5.4.

![Figure 12: Proposed System Level Shallow Water Wave Energy Generation Array](image)

Increased energy absorption will occur due to having more devices acting upon each wave, similar to deep water systems. By placing two or more devices in close proximity constructive interference can occur resulting in recovery of wasted energy\(^2,41\). Also, the instantaneous power transmitted to the Energy Storage, Inverter, and Filter System can be cleaned up and leveled out as the power lows of one device can be compensated for by the peaks of other devices. A further benefit for a shallow wave set-up would be to ensure continued peak power absorption due to tidal increases and decreases in water depth. By ensuring that the array covers the tidal change in where wave systems would have maximum heave and surge you can ensure you maintain peak power generation. As the shallow wave system is typically near the shore, the A/C voltage can be transmitted without having to boost it or change it to D/C, reducing losses from resistance and leveling the A/C.

### 2.7. Other Concerns – Legalities and Regulations

There are legal considerations that must be understood when deciding how to design and where to place a shallow water energy extraction device.
Many country’s governments, such as the US, England, Sweden, Japan, and China, are currently evaluating new laws and regulations for both near and offshore energy generation devices as builders are communicating with regulatory authorities. As the emerging technology and industry grows new laws will build upon the decisions reached by a variety of sources that oversee portions of areas the ocean wave energy devices operate in. As a starting point a system designer and developer should consult the following list to get background on the necessary regulations that should be adhered to. Additional requirements can vary from state-to-state (and country-to-country)\textsuperscript{7, 27}:

- Army Corps of Engineers, under their authority derived from the Rivers and Harbors Acts
- Coast Guard, as almost any shallow water devices would be in navigable waters
- State and local governments, to comply with local planning and zoning ordinances
- Many federal agencies, which may also require various reviews under their jurisdiction, vis-a-vis the Clean Water Act, Endangered Species Act, Tidal Wetland Act, etc.

Other major federal regulations that must be reviewed and complied with, but not limited to, are as follows:

- Rivers and Harbors Appropriation Act of 1899 (33 USC 403; Chapter 425, March 3, 1899; 30 Stat. 1151)
- The Fish and Wildlife Coordination Act (16 USC 661-667e; 48 Stat. 401)
- The Deepwater Port Act of 1974 (P.L. 93-627):
3. RESULTS / DISCUSSION
In this chapter, calculations will be performed using the formulae presented in Chapter 2 and review the results as applied to data taken from an ideal shallow water location.

3.1. Near-Shore Piezoelectric Converter
The overall amount of energy gained would depend upon the efficiency of the converter used and the location and intensity of waves. Using the formulas and concepts discussed in Chapter 2, a year’s raw wave data was taken from the Coastal Data Information Program (CDIP) – at 019 POINT ARGUELLO HARBOR INNER, CA - INNER HARBOR BASIN\(^6\) and used to evaluate the shallow wave damper/piezo-generator model. This area resembles an ideal shallow water wave location and wave data for one year is located in APPENDIX 5. The data was tabulated to evaluate the mean, min, and max for each measurement. The wave energy and power were then tabulated using equations (1) – (4).

Evaluation of the wave data (height and power) in mini-Tab shows that shallow wave data appears to fit a Log-Normal curve (Figures 13 and 14). This aligns with what has been observed in evaluation of shallow wave data examined by Fournier, Alain, Reeves\(^{18}\), and Oohi\(^{33}\), which differs from deep wave data (wave distribution is Gaussian in nature). The data shifts to the left, showing that there are more relative days of calm (flat) waves and fewer days of storm surge. Interestingly, though, it appears that the wave period fits a Weibull distribution better (Figure 15). This could be a further area for research but will not be explored in this paper.
Figure 13: Probability Plot of Shallow Wave Power (1 year)

Figure 14: Probability Plot of Shallow Wave Heights (1 year)
For each wave spectrum data point, the ideal damper volume was next calculated using equation (10). Next the data was compared for using a sphere vs. a cylinder for determining each \( F_D \) and \( F_L \), equation (5), from the projected areas, as shown in Tables 2 and 3. For the damper volume, it is assumed that the mid-point of the floating body is always at \( H_s \), and that the cylinder height = 2\( H_s \). Depth is the depth of the water to the SWL. \( T_a \) is the effective wave period. \( L \) is the length of the wave. \( u \) and \( w \) are the wave velocities, equations (6) and (7). Theta is the wave phase (see APPENDIX 3).

### Table 2: Wave Data – Sphere Damper

<table>
<thead>
<tr>
<th>Shallow water (( d/L &lt; 1/20 ))</th>
<th>( H_s )</th>
<th>( \text{Dept} )</th>
<th>( T_a )</th>
<th>( L )</th>
<th>Volume of ideal damper</th>
<th>Radius of Spher e</th>
<th>( u ) (( \theta = 0 ))</th>
<th>( F_d ) (( \theta = 0 ))</th>
<th>( w ) (( \theta = \pi/2 ))</th>
<th>( F_l ) (( \theta = \pi/2 ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m )</td>
<td>( m )</td>
<td>( \text{sec} )</td>
<td>( m^3 )</td>
<td>( m )</td>
<td>( m^3/s^2 )</td>
<td>( m/s )</td>
<td>( km/s^2 )</td>
<td>( km/s^2 )</td>
<td>( km/s^2 )</td>
<td></td>
</tr>
<tr>
<td>Mean:</td>
<td>0.31</td>
<td>2.23</td>
<td>8.35</td>
<td>110.15</td>
<td>677.35</td>
<td>5.38</td>
<td>0.326</td>
<td>1399.72</td>
<td>0.117</td>
<td>1047.94</td>
</tr>
<tr>
<td>Min:</td>
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<td>4.58</td>
<td>32.72</td>
<td>230.78</td>
<td>3.81</td>
<td>0.175</td>
<td>205.04</td>
<td>0.065</td>
<td>199.41</td>
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<tr>
<td>Max:</td>
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<td>3.32</td>
<td>11.76</td>
<td>215.74</td>
<td>2401.62</td>
<td>8.31</td>
<td>0.644</td>
<td>8452.64</td>
<td>0.335</td>
<td>7122.26</td>
</tr>
</tbody>
</table>
Table 3: Wave Data – Cylinder Damper

<table>
<thead>
<tr>
<th>Shallow water (d/L &lt; 1/20)</th>
<th>Hs</th>
<th>Depth</th>
<th>Ta</th>
<th>L</th>
<th>Volume of ideal damper</th>
<th>Radius of Cylinder</th>
<th>u (theta = 0)</th>
<th>Fd (theta = 0)</th>
<th>w (theta = pi/2)</th>
<th>Fl (theta = pi/2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m</td>
<td>m</td>
<td>sec</td>
<td>m</td>
<td>m^3</td>
<td>m</td>
<td>m/s</td>
<td>kgm/s^2</td>
<td>m/s</td>
<td>kgm/s^2</td>
</tr>
<tr>
<td>Mean:</td>
<td>0.31</td>
<td>2.23</td>
<td>8.35</td>
<td>110.15</td>
<td>677.35</td>
<td>18.55</td>
<td>0.326</td>
<td>832.81</td>
<td>0.117</td>
<td>1006.33</td>
</tr>
<tr>
<td>Min:</td>
<td>0.17</td>
<td>0.98</td>
<td>4.58</td>
<td>32.72</td>
<td>230.78</td>
<td>10.17</td>
<td>0.175</td>
<td>104.86</td>
<td>0.065</td>
<td>296.09</td>
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<tr>
<td>Max:</td>
<td>0.64</td>
<td>3.32</td>
<td>11.76</td>
<td>215.74</td>
<td>2401.62</td>
<td>26.13</td>
<td>0.644</td>
<td>5448.12</td>
<td>0.335</td>
<td>4196.45</td>
</tr>
</tbody>
</table>

At first comparison of Table 2: Sphere to Table 3: Cylinder the following observations can be made. The calculated volume of the ideal damper is very large. This is desired as the damper will be able to absorb a large enough bandwidth of wave frequencies in the given wave spectrum\(^{16}\). Initially it also appears that the sphere shaped volume is better at capturing a larger \(F_D\) and \(F_L\) from the incoming wave spectrum. But there is a problem in that the proposed sphere radius exceeds depth of water that is being used to evaluate this model.

To fix this Table 2 should be adjusted to have the maximum sphere radius be no larger than the minimum water depth, in this case 0.98 meters (see Table 4).

Table 4: Wave Data – Sphere Damper, Radius Equal to Min Depth

<table>
<thead>
<tr>
<th>Shallow water (d/L &lt; 1/20)</th>
<th>Hs</th>
<th>Depth</th>
<th>Ta</th>
<th>L</th>
<th>Volume of ideal damper</th>
<th>Radius of Sphere</th>
<th>u (theta = 0)</th>
<th>Fd (theta = 0)</th>
<th>w (theta = pi/2)</th>
<th>Fl (theta = pi/2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m</td>
<td>m</td>
<td>sec</td>
<td>m</td>
<td>m^3</td>
<td>m</td>
<td>m/s</td>
<td>kgm/s^2</td>
<td>m/s</td>
<td>kgm/s^2</td>
</tr>
<tr>
<td>Mean:</td>
<td>0.31</td>
<td>2.23</td>
<td>8.35</td>
<td>110.15</td>
<td>3.94</td>
<td>0.98</td>
<td>0.326</td>
<td>43.27</td>
<td>0.117</td>
<td>33.66</td>
</tr>
<tr>
<td>Min:</td>
<td>0.17</td>
<td>0.98</td>
<td>4.58</td>
<td>32.72</td>
<td>3.94</td>
<td>0.98</td>
<td>0.175</td>
<td>11.87</td>
<td>0.065</td>
<td>9.80</td>
</tr>
<tr>
<td>Max:</td>
<td>0.64</td>
<td>3.32</td>
<td>11.76</td>
<td>215.74</td>
<td>3.94</td>
<td>0.98</td>
<td>0.644</td>
<td>161.25</td>
<td>0.335</td>
<td>261.02</td>
</tr>
</tbody>
</table>

Reducing the sphere radius by this much effectively reduces the mean volume of the ideal damper by 99.4% and the mean forces \(F_D\) and \(F_L\) by 97%, effectively making the cylinder win out.
Table 5: Wave Data – Cylinder Damper, Height Equal to Twice Max. Hs

| Shallow water (d/L < 1/20) | Hs | Depth | Ta | L | Volume of ideal damper | Radius of Cylinder | u (theta = 0) | Fd (theta = 0) | w (theta = pi/2) | Fl (theta = pi/2) |
|---------------------------|----|-------|----|---|------------------------|-------------------|--------|-------------|--------------|----------------|------------------|
| Mean                      | 0.31 | 2.23 | 8.35 | 110.15 | 2401.62 | 26.13 | 0.326 | 1164.21 | 0.117 | 2074.20 |
| Min                       | 0.17 | 0.98 | 4.58 | 32.72 | 2401.62 | 26.13 | 0.175 | 166.41 | 0.065 | 603.80 |
| Max                       | 0.64 | 3.32 | 11.76 | 215.74 | 2401.62 | 26.13 | 0.644 | 8365.58 | 0.335 | 16082.57 |

Additionally, the submerged portion of the cylinder’s height (equal to Hs) at the maximum calculated height should be taken advantage of as it is still less than the minimum water depth (Table 5). By increasing the damper volume to the maximum value (2401.62 m³) the mean forces F_D and F_L increase by 29% and 51.5% respectively.

Next the maximum allowable force that the piezo-device can withstand before deforming plastically need to be evaluated. In Chapter 2.3, for a large stack of PZT disks it was found that the force necessary to begin to plastically deform the stack was F_D = 3.8 N and F_L = 8250 N. This is much less than the model’s maximum forces acting upon either the ideal cylinder or spherical volumes, with the limiting factor being the bending force (F_D). This is due primarily to the high stiffness of the PZT (6.3*10^10 GPa).

To safely withstand this level of force one should either decrease the size of the effective damper volume or increase the number of piezo rods. As increasing the number of rods would modify the one-rod model by having to split up the effect of the forces across each of the rods it is recommended to reduce the size of the volume into a safe range for a device. For the sphere (Table 6), the volume should be reduced from 3.9 m³ (0.98m radius) to 0.013 m³ (0.15m radius) to meet the max F_D requirements; the max F_L is much less than the allowable F_L. For the cylinder (Table 7), the volume should be reduced from 2401.62 m³ (26.13m radius, 0.98m height) to 0.00037 m³ (0.011m radius, 0.98m height) to meet the max F_D requirements.
Table 6: Wave Data – Sphere Damper, Min Radius for Acceptable $F_D$

<table>
<thead>
<tr>
<th>Shallow water (d/L &lt; 1/20)</th>
<th>$H_s$</th>
<th>Volume of ideal damper</th>
<th>Radius of Sphere</th>
<th>Active Volume of Rod</th>
<th>$u$ (theta = 0)</th>
<th>$F_d$ (theta = 0)</th>
<th>$w$ (theta = pi/2)</th>
<th>$F_l$ (theta = pi/2)</th>
<th>$u$ (theta = pi)</th>
<th>$F_d$ (theta = pi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean:</td>
<td>0.31</td>
<td>0.013</td>
<td>0.15</td>
<td>2.23</td>
<td>0.33</td>
<td>1.00</td>
<td>0.117</td>
<td>0.78</td>
<td>-0.326</td>
<td>1.00</td>
</tr>
<tr>
<td>Min:</td>
<td>0.17</td>
<td>0.013</td>
<td>0.15</td>
<td>0.98</td>
<td>0.17</td>
<td>0.27</td>
<td>0.065</td>
<td>0.23</td>
<td>-0.644</td>
<td>0.27</td>
</tr>
<tr>
<td>Max:</td>
<td>0.64</td>
<td>0.013</td>
<td>0.15</td>
<td>3.32</td>
<td>0.64</td>
<td>3.71</td>
<td>0.335</td>
<td>6.01</td>
<td>-0.175</td>
<td>3.71</td>
</tr>
</tbody>
</table>

Table 7: Wave Data – Cylinder Damper, Min Radius for Acceptable $F_D$

<table>
<thead>
<tr>
<th>Shallow water (d/L &lt; 1/20)</th>
<th>$H_s$</th>
<th>Volume of ideal damper</th>
<th>Radius of Cylinder</th>
<th>Active Volume of Rod</th>
<th>$u$ (theta = 0)</th>
<th>$F_d$ (theta = 0)</th>
<th>$w$ (theta = pi/2)</th>
<th>$F_l$ (theta = pi/2)</th>
<th>$u$ (theta = pi)</th>
<th>$F_d$ (theta = pi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean:</td>
<td>0.31</td>
<td>0.00037</td>
<td>0.011</td>
<td>2.23</td>
<td>0.33</td>
<td>0.49</td>
<td>0.12</td>
<td>0.0004</td>
<td>-0.33</td>
<td>0.48</td>
</tr>
<tr>
<td>Min:</td>
<td>0.17</td>
<td>0.00037</td>
<td>0.011</td>
<td>0.98</td>
<td>0.17</td>
<td>0.07</td>
<td>0.06</td>
<td>0.0001</td>
<td>-0.64</td>
<td>0.07</td>
</tr>
<tr>
<td>Max:</td>
<td>0.64</td>
<td>0.00037</td>
<td>0.011</td>
<td>3.32</td>
<td>0.64</td>
<td>3.52</td>
<td>0.33</td>
<td>0.0029</td>
<td>-0.17</td>
<td>3.52</td>
</tr>
</tbody>
</table>

By evaluating the application of equations (16) and (17) it can be seen how much energy each device would generate. As the apparatus is only designed to act in tension and bending $F_l$ at theta = 3/2 pi should be not used, as it is a compressive force and would result in a loss as well as potentially damaging the device as it was not designed to act in compression.

Comparison of Table 8 and 9 shows that the sphere, due to the increased bending strain results in higher mean power ($P_X'$) generated than the cylinder, approximately 3x more. This is due to the larger projected area of the sphere causing increased drag force on the rod. The mean $P_Z'$ power is found to be very low in both cases. This is due to the small projected damper area not being able to generate enough lift force to overcome the stiffness, $Y_m$, and weight of the rod to cause a strain and generate sufficient power.
To see how efficient our device is the mean total device power (PP) per wave can be compared against the mean wave power (P) per wave. The sphere shape damper device is shown to win out when shallow water system constraints are applied in this model. As shown in Tables 10 and 11, the mean total power (PP) was summed from each data point for each portion of the wave by combining the output power resulting from the drag force summed with the power generated during the heave force to generate total power for the wave. The wave power (P) was then compared to the summed device power (PP). The CDIP mean P for a year of data is 454 Watts/meter of wave. This is due to the small wave heights and shallow water (depth). The total mean PP was found to be 0.0378 Watts (sphere) and 0.0129 Watts (cylinder). Each mean PP was then further reduced to 50% PP to account for the 80% efficiency of PZT in converting mechanical energy to electricity and to conservatively account for friction, transmission loss, and other losses. The 50% mean PP is 0.0189 W for the sphere and 0.0064 W for the cylinder. These power results are aligned with those found by Thiam and Pierce when they estimated that 50cm$^3$ of PZT material would be need to be strained 0.001 m to produce 1 Watt.

### Table 8: Wave Data – Sphere Damper, Power Generation

<table>
<thead>
<tr>
<th>Shallow water (d/L &lt; 1/20)</th>
<th>Hs</th>
<th>$u$ (theta = 0)</th>
<th>Bending Strain</th>
<th>$w$ (theta = pi/2)</th>
<th>Tensile Strain</th>
<th>$u$ (theta = pi)</th>
<th>Bending Strain</th>
<th>$w$ (theta = pi/2)</th>
<th>Tensile Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean:</td>
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<td>Min:</td>
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<td>0.17</td>
<td>0.00006</td>
<td>0.001</td>
<td>0.065</td>
<td>4.49E-08</td>
<td>1.33E-09</td>
<td>-0.644</td>
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<tr>
<td>Max:</td>
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<td>0.64</td>
<td>0.00093</td>
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<td>0.335</td>
<td>1.88E-06</td>
<td>9.38E-06</td>
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<td>0.00077</td>
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</table>

### Table 9: Wave Data – Cylinder Damper, Power Generation

<table>
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<tr>
<th>Shallow water (d/L &lt; 1/20)</th>
<th>Hs</th>
<th>$u$ (theta = 0)</th>
<th>Bending Strain</th>
<th>$w$ (theta = pi/2)</th>
<th>Tensile Strain</th>
<th>$u$ (theta = pi)</th>
<th>Bending Strain</th>
<th>$w$ (theta = pi/2)</th>
<th>Tensile Strain</th>
</tr>
</thead>
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<tr>
<td>Min:</td>
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<td>0.17</td>
<td>0.00002</td>
<td>0.000</td>
<td>0.06</td>
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<td>0.33</td>
<td>8.95E-10</td>
<td>2.12E-12</td>
<td>-0.17</td>
<td>0.00073</td>
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</table>
Table 10: Wave Data – Sphere Damper, Total Power Generation and Efficiency

<table>
<thead>
<tr>
<th>Shallow water (d/L &lt; 1/20)</th>
<th>P = Nonlinear Wave Power</th>
<th>Total PX'</th>
<th>Total PZ'</th>
<th>Total PP</th>
<th>50% Total PP</th>
<th>Efficiency</th>
<th>Array of 100</th>
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<tbody>
<tr>
<td></td>
<td>W/m</td>
<td>W</td>
<td>W</td>
<td>W</td>
<td>%</td>
<td>W</td>
<td></td>
</tr>
<tr>
<td>Mean:</td>
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<td>1.599E-07</td>
<td>0.0378</td>
<td>0.0169</td>
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<tr>
<td>Min:</td>
<td>126.88</td>
<td>0.002</td>
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<td>0.026%</td>
<td>30.976</td>
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</tbody>
</table>

Table 11: Wave Data – Cylinder Damper, Total Power Generation and Efficiency

<table>
<thead>
<tr>
<th>Shallow water (d/L &lt; 1/20)</th>
<th>P = Nonlinear Wave Power</th>
<th>Total PX'</th>
<th>Total PZ'</th>
<th>Total PP</th>
<th>50% Total PP</th>
<th>Efficiency</th>
<th>Array of 100</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W/m</td>
<td>W</td>
<td>W</td>
<td>W</td>
<td>%</td>
<td>W</td>
<td></td>
</tr>
<tr>
<td>Mean:</td>
<td>454.88</td>
<td>0.0129</td>
<td>3.649E-14</td>
<td>0.0129</td>
<td>0.0064</td>
<td>0.000029%</td>
<td>0.645</td>
</tr>
<tr>
<td>Min:</td>
<td>126.88</td>
<td>0.0001</td>
<td>3.187E-16</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.00046%</td>
<td>0.007</td>
</tr>
<tr>
<td>Max:</td>
<td>2028.36</td>
<td>0.5574</td>
<td>2.116E-12</td>
<td>0.5574</td>
<td>0.2787</td>
<td>0.016152%</td>
<td>27.872</td>
</tr>
</tbody>
</table>

To try to offset the loss of efficiency the devices could be deployed in an array, in this case 100 devices, to absorb more energy from the wave. Ideally the devices would be laid out in a line and spaced to not affect each other while being close enough to affect the entire wave width. The array would ideally be positioned to be perpendicular to the incoming wave direction and each device (moored) at the same depth. By increasing the number of devices that absorb the incoming wave’s energy an increase in the mean power is generated; 1.89 W for the sphere array and 0.65 W for the cylinder array.

To put the amount of power generated in perspective the anticipated the rough total power per year for the spherical array can be calculated. Using the mean wave period, T, of 8.35 seconds the total number of waves for 365 days (31,536,000 seconds) can be calculated to be 722,339,640 waves. By multiplying this by the mean power per wave of 1.89W we find that 1.36 gigawatts are generated. This by all accounts is a very large amount of energy generated. Alternatively, if it is desired to be even more conservative the min power generated (0.092 W) can be used instead of our average power and it is found that 66 megawatts are still generated annually, which is a large amount of energy.
3.2. Comparison to Alternatives and Costs

This chapter will discuss the expected and unexpected costs of shallow water, near shore WECs compared to other methods of producing energy.

In the generation of electricity from fossil fuels as a resource for public consumption in the form of a utility there rise two forms of externalities: Cost and Benefit. Cost externalities, defined in *Managerial Economics* (Keat, 2008), are defined as an unaccounted for cost that the producer does not always have to pay as part of production. Benefit externalities are costs that are not compensated. In fossil fuel electricity generation cost externalities come in forms such as pollution and potentially climate change (Riversedge, 2010). These types of externalities are very difficult to evaluate due to their nature. It is difficult to measure the extent of pollution from electricity generation and its effects on nature other than observing obvious symptoms from general pollution such as acid rain, carbon dioxide increase/global warming, and chemical invasion in drinking water and attempting to apply a ratio based on the global fossil fuel consumption and making estimates (Wikipedia, 2010). Additional costs such as purchase of the fossil fuel natural resources, shipment to an electric plant, and waste heat through inefficiencies in the transformation of the fuel to electricity all add to the overall costs of the end product.

Externalities can be overcome either through government regulation and credits/taxes (Keat, 2008, pg. 526), by expensive technology, or through utilizing alternative energy forms that do not result in these externalities, such as near-shore wave energy. Shallow water wave energy generation, one form of alternative energy, can create usable energy in the form of electricity efficiently, renewably, and competitively as compared to fossil fuels and other alternative fuels.

To understand the economics of various alternative energies one can refer to Twidell and Weir’s “Economics of Renewable Energy Resources, Ch. 13” which evaluates various different energy forms (i.e. wind, water waves and hydro, solar, etc.) for total lifecycle costs.
cost and considerations for use with a focus on wave energy. To understand the cost of a technology you need to evaluate various factors. These include understanding Initial Capital required to start up, Interest during construction, Refurbishing and replanting during the life of the equipment, Decommissioning Costs, Operation and Maintenance Costs, Resource Availability, Plant (equipment) availability, Life of the equipment, Break-even Costs, Rated Performance, Rate of Return, and other miscellaneous costs. Ideally though what matters most is efficiency; do you get the most out of what you put into the machine? To guide consideration of these factors it is recommended to use Muller and Wallace’s “7-Key Challenges”\textsuperscript{30} (Table 12) to further compartmentalize the discussion and make a comparison between fossil fuel energy generation and ocean wave generation:

<table>
<thead>
<tr>
<th>Challenge</th>
<th>Priority advances</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predictability</td>
<td>Understanding the resource and device interaction such that it delivers a predicted design performance...</td>
</tr>
<tr>
<td>Manufacturability</td>
<td>Understanding the consequences of increasing scale from 1/100 to full size</td>
</tr>
<tr>
<td>Installability</td>
<td>Establishing fabrication, transport and installation infrastructure</td>
</tr>
<tr>
<td>Operability</td>
<td>Improving offshore access, operation and maintenance</td>
</tr>
<tr>
<td>Sustainability</td>
<td>Establishing standards, testing, proving and certification methods and operating to them</td>
</tr>
<tr>
<td>Reliability</td>
<td>Improving coating, sealing, monitoring and reliability in marine environment</td>
</tr>
<tr>
<td>Affordability</td>
<td>Developing equitable means of lifetime costing and performance appraisal</td>
</tr>
</tbody>
</table>

Predictability – The energy amounts that can be extracted from fuels are well understood and finite. From (Bioenergy, 2010)\textsuperscript{4}

- Barrel of oil equivalent (boe) = approx. 6.1 GJ (5.8 million Btu), equivalent to 1,700 kWh.
- Natural gas: HHV = 1027 Btu/ft$^3$ = 38.3 MJ/m$^3$; LHV = 930 Btu/ft$^3$ = 34.6 MJ/m$^3$. 

47
Wave devices currently are designed usually to take advantage of a specific feature of waves (heave, surge-sway, and combination) (Mueller, Wallace, 2008)\textsuperscript{30} which can be seasonal and change throughout the year (see APPENDIX 5) and vary from location to location. Additionally, a near-shore device would have to take into account the changing shoreline/environment which makes it an increasingly difficult area to predict wave energy output and design a device to extract it. Fossil fuels as a more predictable and stable resource would have the advantage in this category and be lower cost, for the time being.

**Manufacturability** – Modern fossil fuel and hydro-electric power plants have been around for many, many years and the designs are well established and leaned out. But they are usually large (to meet the needs of the grid) and take years to design, build, and install. Multiple regulations exist that must be adhered to and can drive up costs.

Wave power generation devices, on the other hand, have only been around for approx. 50 years and are still being developed. The difficulty in wave power generation is that they have to be designed to work in an unpredictable, caustic environment; waves are not constant and vary in intensity and salt water corrodes many materials. Investment will need to be large to catch-up to the efficiency of the plants. New tools and technology will need this investment to meet the environmental challenges. But these systems can be tailored to meet a specific power generation based upon the area and innovations are not being stifled by regulations.

**Installability and Survivability** – Large fossil fuel power-plants are expensive and take up a lot of space. Once built they last for years and years with regular maintenance. Some of the oldest still operating coal power-plants in the US were built in 1921.

Ocean wave power plants require installation too and have costs. As a baseline for comparison, offshore wind farms cost 50 to 100% more to install compared to those on
land. Usually offshore systems are either designed to be moored to the ocean floor or attached to another stable vessel or construction to keep them from floating away. This leads to difficulties such as ocean depths, potential to lose a device if the attachment breaks, etc. From (Harris, 2010), then there are environmental issues. Placing large man-made structures in the oceans will clearly have some effect on marine life. Tidal energy generators present perhaps the biggest challenges. Machinery in these structures can kill fish and impede their migration to spawning areas. Tidal generators also interfere with the normal flushing of silt and other dissolved pollutants. This affects water quality, which in turn affects bird and fish life. Some of the major concerns associated with ocean power are variable intensity, limited survivability of equipment, navigation and sea-space concerns, and release of lubricants.

To overcome these concerns, the array would have to be moored near the shore to keep it from floating away. Being near the shore would help to keep costs down by not requiring long distance transmission wires. Additionally, an ideal shore would have to be identified where the influence of the tides would be minimized to ensure maximum wave energy transmission. Lower tides would result in smaller waves due to drag from the ocean bottom. The rubber damper encasing the array would resist the salt water corrosion. Nor would there be any oils or lubricants that could leak. This would keep the ocean environment safe. Ideally, the rubber could be translucent and minimize the impact on the ocean life. When both models are compared holistically, it can be seen that the shallow wave device can potentially result in fewer costs and have higher longevity with less environmental impact.

Operability – (Wikipedia, 2010) references that typical thermal efficiency for electrical generators in the industry is around 33% for coal and oil-fired plants, and up to 50% for combined-cycle gas-fired plants. Plants designed to achieve peak efficiency while operating at capacity will be less efficient when operating off-design (i.e. temperatures too low.)
Ocean wave generators will have a variable output due to the variation of the wave input. Therefore they have to be designed to be attuned to efficiently extract energy from a range of wave inputs and selectively installed in locations that have that average range. If waves are applied as inputs that are too big, they risk damaging the device. Too small and you may not get enough energy out. Some wave machinery have already extremely high efficiencies (Salter Duck - ~81% in controlled experiments\(^{31}\)). This shows that with the right technology and application in a specific spectrum of waves you should be able to compete with fossil fuel plants.

**Reliability and Affordability** –

It can be anticipated that by scaling high efficiency wave generators electricity could be produced at a cost comparable to wind-driven turbines, which produce energy at about $0.045 / kWh, though current state of WECs produce energy at an average projected/assessed cost of $0.075/ kWh\(^{29}\). Additionally, the ocean wave “fuel” is essentially free and renewable and will not run out but it is an unpredictable fuel.

Meyer makes the comparison, “In comparison, electricity generated by large scale coal burning power plants costs about $0.026 / kWh. Combined-cycle natural gas turbine technology, the primary source of new electric power capacity is about 3 cents per kilowatt hour or higher. It is not unusual to average costs of $0.05 / kWh and up for municipal utilities districts\(^{29}\).” Additionally, fossil fuel is generally considered a finite resource. As current resources are depleted, if the demand stays stable, the price for fossil fuels would be expected to increase. This is already being seen. From (Devices, 2009)\(^{10}\), the author comments that, “even though wave energy is at the very beginning of the manufacturing learning curve, capital costs per net kW are already down in the range of wind energy devices, and below solar. In areas of higher power costs, such as diesel-based communities not connected to the grid, investment returns from wave energy projects are potentially very attractive.”
Now that the baseline power generation costs are understood, there are additional costs that need to be factored. The cost to transmit energy via power lines needs to be considered as well. Above ground lines cost around $10 per foot and underground (and submerged) lines cost in the range of $20 to $40 per foot for installation plus yearly maintenance. Long-distance transmission of electricity (thousands of kilometers) is cheap and efficient, with costs of US$0.005–$0.02/kWh, with transmission and distribution losses in the USA were estimated at 6.6%\(^\text{12}\). This makes a strong case for using near-shore energy generation (within 1 mile of the shore line) as opposed to off-shore (>1 mile from the shoreline) as there are fewer initial costs involved with installation and less required maintenance. Additionally, less transmission cable leads to better overall efficiency as you will have lower distribution losses.

From (Thiam, Pierce, 2010)\(^\text{45}\) a rough estimate of energy from piezoelectric material is 1 Watt from 50 cubic centimeters resulting from a 0.001” tensile strain (from a disk of common PZT). This shows a great efficiency that a small movement creates a lot of electricity. To achieve energy equal to 1 barrel of oil (1700 kWh) this single piece of crystal would have to be stretched 1,700,000 times in one hour. But if an array of 1000 crystals were created and linked together, then each crystal in the array would only have to be flexed 1700 times in one hour.

What this shows is that through selection of the crystal properties and sizes, by combining in an array you can maximize the power output. Losses in the system would be from: friction; loss of wave energy from wave to damper, and damper to the crystal, and crystal to the energy storage device via transmission line.

Many piezoelectric ceramics and crystals are proprietary and this would influence the cost of the apparatus. Additional costs in the form of royalties from patents may have to be paid. But the apparatus is simple and scalable to an application. This scalability is key to off-setting the costs required to compete with large fossil fuel power plants.
A near-shore wave energy apparatus should be able to compete with a fossil fuel power plant. This is because it would not generate the cost externalities that a fossil fuel plant does (in the form of pollution), it uses “free” fuel in the form of renewable ocean waves, and through proper engineering and manufacturing can have a low initial cost to build and install. Referring to Fig. 16 from *Managerial Economics*[^24], a fossil fuel plant would operate at Marginal Cost (MCs) having a higher cost (P) while a wave energy plant could operate at Marginal Cost of Product (MCp) with a lower cost (P1) it will not have to pay for the additional cost of the externalities.

![Figure 16: Impact of the Marginal Cost of Pollution on Price[^24]](image)

MCp = Marginal Cost of Product; MCpol = is Marginal Cost of Pollution (externality); MCs = summation of MCp and MCpol; P1 = Price of Product; Popt = price of product plus cost if externalities included; D = Demand, Q = units produced; Q1 is qty. produced at price P1; Popt = Optimal price if all costs included.

In a higher level comparison where the output energy of a fossil fuel plant is equal to a near-shore, shallow water wave energy plant these lower costs would enable the near-shore, shallow water wave plant to ultimately make higher revenue over the life of the plant.
4. CONCLUSION

4.1. Conclusions
Waves are excellent sources of energy, are a natural resource, and are renewable. Waves in shallow water can be one of the best ways to capture this energy as this is when the wave energy is at its maximum. Wave energy can be categorized in both potential and kinetic, where the potential energy is a factor of the wave amplitude and displacement and the kinetic energy is a factor of the translation of the particles. These energies can be captured using opposing forces such as drag and buoyancy. How much energy is captured depends upon a number of factors: wave translation, wave height, the number of waves in a set period, the type of converter used and its efficiency of capturing both the potential and kinetic wave energy, as well as the changing shape of the shallow water bottom and if you are near shore or not.

Wave energy consists of both linear and non-linear waves. These waves overlap each other and combine energy through superposition. A device can take advantage of this to absorb the maximum amount of wave energy, if it is an ideal damper, as well as symmetrically shaped to absorb input energy from any direction. There are limitations on the size of the volume and how much energy can be absorbed. A damper should be both an ideal optimum wave interferer (tuned to resonance and as large as possible) and have an optimum ratio of energy extraction due to volume (Budal’s Upper Bound). Additionally, the size and complexity of a device can drive up costs. A symmetric shape, such as a sphere or cylinder, is preferred as it allows resolution of forces acting on the damper body into drag and buoyancy forces. The maximum size of the damper though is dependent upon the location where it is utilized. In the selected shoreline model, it was found that the damper had a constraint on height where the damper could be no larger than the twice the minimum depth of the location where installed, else the damper would hit the ocean floor and only move when the waves were at their highest.

Energy generation occurs by coupling the damper device to an energy generator. Piezoelectricity is an efficient mechanical generator of electricity, approaching 80% for
PZT, with little mechanical movement required. It was found though that piezo-crystals and ceramics have limitations that make it difficult to use in this application. Piezo-crystals and ceramics have manufacturing limitations that constrain size and shape, which required building a stack of piezo-disks into a 3.32m high by 113.1 mm² rod (3.32 m being the maximum depth of the system). PZT is also very stiff, having a very high modulus of elasticity (63 GPa). This resulted in a limiting of the maximum amount of bending force that the piezo stack could safely withstand before plastically deforming ($F_L = 3.8$ N, compared to the maximum tensile force of $F_D = 8250$ N).

Other considerations were also evaluated to help guide designing a shallow water system. Design guidelines were developed to understand the different types of systems that can be built as well as the pros and cons. It was found that a floating, tethered system that makes use of at least 3 degrees of freedom (heave, surge, sway) is preferred as it would have stability, adaptability, and simplicity. Additionally, analysis of the wave spectrum would help a designer “tune” the absorber for maximum efficiency. Other considerations should be what the total system would look like. It is recommended that the system be developed to have an array of WECs to not only capture additional energy per unit area but also as a method to support energy gaps during peaks and valleys of the wave flow. Devices that are near the shoreline can take advantage of the fact that there is less transmission loss in the form of heat when sending the electricity in short cables to a central storage location; and this is a benefit over off shore WECs. The storage location should take advantage of both a variable energy absorber/discharger, like a fly wheel or ultra-capacitor, to rapidly take in the inputs from the different array components as well as use a battery pack to ensure long term level supply to the energy grid.

The environment will play a large driver in the design of the WEC. As the ocean is a harsh environment it is highly recommended that the WEC be designed not only to be sturdy, with marine grade materials, but also sustainable and eco-friendly. Through scheduled inspection and repairs the WEC should have a long and useful life. Ocean
and river regulations will help direct not only placement of a WEC device but also what materials can be used and how often inspections should occur. Excessive and difficult regulations can drive increased cost into the lifecycle of the WEC installation and should be evaluated as a factor into the cost model.

Once the system was designed, a model was created using ideal shallow water data from the CDIP for a location in southern California. Ideal sphere and cylinder equations were calculated using equation (10) to determine that a maximum volume of 2401.6 m$^3$ would be ideal damper size for the system, and the largest $F_D$ and $F_L$ were calculated for each data point. Constraints were next added on the system for the size of the damper and again to maximize the drag and lift forces. It was found initially that the cylinder was the better shape as it had the most flexibility for higher drag and lift forces. Due to the limitations of the piezoelectric design, primarily from bending stress, though, the volumes had to reduce to 0.013 and $3.7 \times 10^{-4}$ m$^3$ for the sphere and cylinder respectively; a reduction of 99.995% and 99.99998%. The sphere ultimately won out, absorbing the most energy and transmitting it to the piezo rod for electricity generation.

A comparison of efficiency of wave input power, $P$, was compared to the consolidated piezo rod output power, $PP$, for both the sphere and cylinder designs as a stand-alone device and an array of 100 WECs. The sphere array had the highest mean power of 1.89W, with a potential peak power of 30.9W, compared to the cylinder array’s mean power 0.645W and peak power of 27.9W. By comparison, if it was desired to be very conservative if only the minimum power was generated by the sphere array it would result in 0.092W being generated. The sphere model had a very low efficiency of 0.0009% when compared to other WECs, like the Salter Duck at 81%, 33% for coal and oil plants, and 50% combined cycle-gas fired plants. But, even though it was low efficiency the sphere model produces a respectable 1.36 gigawatts average output annually.
4.2. Recommendations
This chapter will discuss recommendations and suggested improvements for to proposed model and shallow water WECs. Additionally, future proposed research will be recommended.

4.2.1. Improvements
The proposed shallow water WEC piezo system could be redesigned to try to increase efficiency further. The model could be changed to take advantage of the increased capability of the piezo rod device in tension as opposed to bending. If the system was redesigned so that an ideal damper (with a very large volume) for the wave system could be coupled with the piezo rod energy generator that is only ever in tension the results may be much more favorable and this should be evaluated. An example of this would be to mount the piezo rod to a base that swivels and use a pin mechanism to allow the rod/damper to adjust in both the X’ and Z’ directions for tide, angle of wave attack, and wave height. In this way the $F_D$ and $F_L$ forces would sum as a resultant through the center of a sphere damper and apply a tension force on the rod (see figure 17). But a comparison of efficiency would have to be performed to see if more power could be generated in this fashion.
Additionally, the selection of piezo-material is an area that should be looked into. The selected piezo-crystal or ceramic should have the highest $K$ and lowest $E$ possible as these have the largest effect on the ability to generate electricity.

Finally, the clutching mechanism that links the damper to the piezo rod needs to be developed to ensure that the damper grips the rod at the right location in the wave phase.

4.2.2. Considerations

The piezo-energy shallow water WEC is very cheap in comparison to a large power plant or offshore WECs. Offshore WECs and conventional power plants have a large number of life-cycle costs, such as location, maintenance and sustainability, and pollution. These factors play a large part in the total cost model in comparison to the shallow water, near shore WEC array.
While WECs are not generally as stable as conventional power plants using fossil fuels for energy generation they do not have the drawbacks of fossil fuel generation. Currently fossil fuel energy generation is cheap, at approximately $0.026 - $0.05 / kWh while WECs are around $0.07 / kWh. The cost for WEC generated energy is expected to drop rapidly though as higher levels of efficiency are recognized and the cost of research and development recouped. Factoring the benefits as well as being near shore as opposed to offshore, one can expect that with equally efficient WECs, the shallow water near shore system would win out on cost.

4.2.3. Future Research
As mentioned above in Chapter 4.2.1 the model should be reevaluated to consider the piezo-rod to operate only in tension. Additionally, there would be benefit to continue evaluating ideal damper shapes that could be selectively tuned to a selected wave spectrum to increase the amount of absorbed energy. Piezo-materials other than PZT should also be evaluated. And a clutching system that mates the piezo rod to the damper needs to be developed further.

The analytical model should be tested in a shallow water location to verify results empirically. It can be expected that as the data taken by the CDIP and equations considered have been linearized an empirical evaluation could recognize greater energy generation than actually calculated.
REFERENCES / BIBLIOGRAPHY


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http://www.piezo.ws/piezoelectric_actuator_tutorial/Piezo_Design_part2.php


## APPENDICES

### 1. List of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Piezo disk area, meters (m)</td>
</tr>
<tr>
<td>A/C</td>
<td>Alternating current, Volts</td>
</tr>
<tr>
<td>$A_0$</td>
<td>Elevation amplitude of the incident wave, radians</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Factor for beach angle</td>
</tr>
<tr>
<td>C</td>
<td>Wave celerity, m/s</td>
</tr>
<tr>
<td>$C_{d}, C_{l}$</td>
<td>Drag and lift coefficients</td>
</tr>
<tr>
<td>d</td>
<td>Water depth, meters</td>
</tr>
<tr>
<td>D</td>
<td>Demand, $$</td>
</tr>
<tr>
<td>D/C</td>
<td>Direct Current, Volts</td>
</tr>
<tr>
<td>$d_{31}$</td>
<td>Mechanical-to-electrical coupling parameter of the piezoelectric material.</td>
</tr>
<tr>
<td>$d_{33}$</td>
<td>Induced polarization</td>
</tr>
<tr>
<td>DD</td>
<td>Day</td>
</tr>
<tr>
<td>$\Delta L$</td>
<td>Piezo stack displacement in the Z' and X' directions. Delta Ln is displacement of a single disk, meters.</td>
</tr>
<tr>
<td>dL</td>
<td>Change in length L, meters</td>
</tr>
<tr>
<td>Dp</td>
<td>Mean Direction</td>
</tr>
<tr>
<td>E</td>
<td>Per unit area of sea surface stored energy, kg/s²</td>
</tr>
<tr>
<td>$E, Y_m$</td>
<td>Modulus of Elasticity, GPa</td>
</tr>
<tr>
<td>$E_t$</td>
<td>Total wave energy per unit width, kg*m/s²</td>
</tr>
<tr>
<td>f</td>
<td>Wave frequency, Hz</td>
</tr>
<tr>
<td>$F_D$</td>
<td>Drag force, Newtons</td>
</tr>
<tr>
<td>$F_L$</td>
<td>Transverse force, Newtons</td>
</tr>
<tr>
<td>$f_p$</td>
<td>The straining frequency of the piezoelectric material, Hz</td>
</tr>
<tr>
<td>g</td>
<td>Gravity, $= 9.81 \text{ m/s}^2$</td>
</tr>
<tr>
<td>gamma</td>
<td>Factor for destructive wave interference</td>
</tr>
<tr>
<td>H</td>
<td>Wave height, meters</td>
</tr>
<tr>
<td>HH</td>
<td>Hour</td>
</tr>
<tr>
<td>$H_s$</td>
<td>Significant wave height, meters</td>
</tr>
<tr>
<td>I</td>
<td>Moment of Inertia, m⁴</td>
</tr>
<tr>
<td>i</td>
<td>Current, amps</td>
</tr>
<tr>
<td>K</td>
<td>Electromechanical coupling factor, m²/N</td>
</tr>
<tr>
<td>$k_{31}, k_{33}$</td>
<td>Electromechanical coupling efficiency, factor for electric field</td>
</tr>
<tr>
<td>kW</td>
<td>KiloWatt</td>
</tr>
<tr>
<td>kWh</td>
<td>KiloWatt hour</td>
</tr>
<tr>
<td>L</td>
<td>Wave length, meters</td>
</tr>
<tr>
<td>L</td>
<td>Piezo rod length = max d, meters</td>
</tr>
</tbody>
</table>
m Mass, kg
MCp Marginal Cost of Product, $$
M_{pol} Marginal Cost of Pollution (externality), $$
MCs Summation of MCp and MCpo, $$
MN Minute
MO Month
n Number of piezo stack layers
N_{x'} Normal force in X'-direction, Newtons
N_{Z'} Normal force in Z'-direction, Newtons
P' Nonlinear wave power, W/m
p Pressure, atmospheres
PX', PZ' Power output of piezo device
P Price of Product, $$
P_a Absorbed wave power due to an oscillating system, W/m
P_b Budal's upper limit, W/m
P_{opt} Price of product plus cost if externalities included; Optimal price if all costs included, $$
PP Piezoelectric device power; Power per unit volume from piezoelectric material
PZT Lead zirconate titanate
Q Units produced
Q1 Quantity produced at price P1, units
r Radius, meters
s strain
S(t) Wave spectrum, m²/Hz
S a Projected area of a structure, m²
sp Mechanically strain percentage of the piezoelectric material
SWL Still water level, meters
T Wave period, seconds
t Height of the piezo disk, meters
Ta Average Period, seconds
th Piezoelectric material thickness, meters
theta Wave phase, radians
Tp Peak period, in seconds
TW TerraWatt
v Relative velocity of a fluid, m/s
V Volume (of heaving body), m³
V Generated A/C voltage from piezoelectric material, Volts
V_{x'} and V_{Z'} Voltage in the Z' and x' directions, Volts
W Watt
WEC  Wave Energy Converter
X  X-direction, Surge
X'  Resultant of the X and Y directions
Y  Y-direction, Sway
YYYY  Year
z  -d (water depth), meters
Z  Z-direction, Heave
Z'  Z'-direction
 ε  Permittivity.
 εS33  permittivity for dielectric displacement and electric field in direction 3 (parallel to direction in which ceramic element is polarized), under constant strain
u  X component of velocity, m/s
w  Z component of velocity, m/s
 ρ  Density, 1030 kg/m^3 is the mass density of sea water
η  Elevation of the free surface relative to the Still Water Line (SWL), meters
π  pi = 3.14157….
ϑ  Wave phase in radians
ϑ_x'  Max bending stress in X' direction, Newtons/m^2
ϑ_z'  Max stress in Z' direction, Newtons/m^2
v  Y component of velocity, m/s
## 2. Definitions

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average period</td>
<td>In seconds; derived from the zeroth moment divided by the first moment of the reported energy spectrum.</td>
</tr>
<tr>
<td>Benefit externalities</td>
<td>Costs that are not compensated</td>
</tr>
<tr>
<td>Buoyancy</td>
<td>Buoyancy is historically defined by Archimedes Principle: Any object, wholly or partly immersed in a fluid, is buoyed up by a force equal to the weight of the fluid displaced by the object. This results from the fact that fluid pressure increases with depth and from the fact that the increased pressure is exerted in all directions (Pascal's principle) so that there is an unbalanced upward (Lift) force on the bottom of a submerged object.</td>
</tr>
<tr>
<td>Corrosion</td>
<td>Corrosion is caused by the electrochemical reaction in which a metal anode corrodes by oxidation and a cathode undergoes reduction reaction.</td>
</tr>
<tr>
<td>Cost externalities</td>
<td>An unaccounted for cost that the producer does not always have to pay as part of production</td>
</tr>
<tr>
<td>$d_{31}$</td>
<td>Mechanical-to-electrical coupling parameter of the piezoelectric material. Induced polarization in direction 3 (parallel to direction in which ceramic element is polarized) per unit stress applied in direction 1 (perpendicular to direction in which ceramic element is polarized) or induced strain in direction 1 per unit electric field applied in direction 3</td>
</tr>
<tr>
<td>$d_{33}$</td>
<td>Induced polarization in direction 3 (parallel to direction in which ceramic element is polarized) per unit stress applied in direction 3 or induced strain in direction 3 per unit electric field applied in direction 3</td>
</tr>
<tr>
<td>Damper</td>
<td>A device that deadens, restrains, or depresses.</td>
</tr>
<tr>
<td>Depth</td>
<td>Mean sensor depth (meters) at the time of the observation in meters; not corrected for tide. For a pressure sensor, water depth is calculated as the sample mean.</td>
</tr>
<tr>
<td>Drag</td>
<td>Sometimes called fluid resistance, drag is the force that resists the movement of a solid object through a fluid (a liquid or gas). The most familiar form of drag is made up of friction forces, which act parallel to the object's surface, plus pressure forces, which act in a direction perpendicular to the object's surface. For a solid object moving through a fluid, the drag is the component of the net aerodynamic or hydrodynamic force acting in the direction of the movement. The component perpendicular to this direction is considered lift. Therefore drag acts to oppose the motion of the object, and in a powered vehicle it is overcome by thrust.</td>
</tr>
<tr>
<td>Electromechanical coupling factor, $K$</td>
<td>The electromechanical coupling factor, $K$, is an indicator of the effectiveness with which a piezoelectric material converts electrical energy into mechanical energy, or converts mechanical</td>
</tr>
</tbody>
</table>
energy into electrical energy. The first subscript to $K$ denotes the direction along which the electrodes are applied; the second denotes the direction along which the mechanical energy is applied, or developed. A high $K$ usually is desirable for efficient energy conversion.

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heave</td>
<td>The linear vertical (up/down) motion</td>
</tr>
<tr>
<td>$k_{31}$</td>
<td>Electromechanical coupling factor for electric field in direction 3 (parallel to direction in which ceramic element is polarized) and longitudinal vibrations in direction 1 (perpendicular to direction in which ceramic element is polarized)</td>
</tr>
<tr>
<td>$k_{33}$</td>
<td>Electromechanical coupling factor for electric field in direction 3 (parallel to direction in which ceramic element is polarized) and longitudinal vibrations in direction 3</td>
</tr>
<tr>
<td>Line Absorber</td>
<td>If the extension is comparable to or larger than a typical wavelength, the WEC is called a line absorber.</td>
</tr>
<tr>
<td>Mean Direction</td>
<td>Mean direction from which energy is coming at the peak period, in degrees clockwise from true North. (For pressure sensors in deep water, such as at Harvest Platform, we are unable to resolve $D_p$ there when the peak period is less than .14 hz.)</td>
</tr>
<tr>
<td>Peak period</td>
<td>Inverse of the frequency with the highest energy density in the reported spectrum.</td>
</tr>
<tr>
<td>Permittivity</td>
<td>The piezoelectric material’s dielectric constant. $\varepsilon_T$ is the permittivity at constant stress, $\varepsilon_S$ is the permittivity at constant strain. The first subscript to $\varepsilon&gt;$ indicates the direction of the dielectric displacement; the second is the direction of the electric field. $\varepsilon_{S33}$, as an example, is permittivity for dielectric displacement and electric field in direction 3 (parallel to direction in which ceramic element is polarized), under constant strain.</td>
</tr>
<tr>
<td>Point Absorber</td>
<td>If the extension is very small compared to a typical wavelength a WEC is a Point Absorber</td>
</tr>
<tr>
<td>Significant Wave Height</td>
<td>The significant wave height is defined as the average of the highest 33% of the waves. Significant wave height in meters; derived from the “zeroth” moment of the reported energy spectrum. Described as the &quot;average height of the one third highest waves in the record&quot;. The US Army Corps of Engineers, Shore Protection Manual, 3-11, states that a useful estimate of significant wave height in deep water is defined as: $H_s \sim 4*\sigma$, where $\sigma$ is the standard deviation of the wave record. Statistically, the maximum wave height in the record is $H_{\text{max}} \sim 9*H_s/5$.</td>
</tr>
<tr>
<td>Superposition</td>
<td>This states that the irregular pattern of waves can be seen / modeled as a superposition of many regular waves each with its own amplitude, length, period and propagation direction. Measurement data, using significant wave height and zero-crossing wave period as statistical measurement points, is used to</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>define the specific regular waves that will result in a representative wave regime.</td>
<td></td>
</tr>
<tr>
<td>Surge</td>
<td>The linear longitudinal (front/back) motion.</td>
</tr>
<tr>
<td>Sway</td>
<td>The linear lateral (side-to-side) motion</td>
</tr>
<tr>
<td>Terawatt (TW)</td>
<td>1012 Watts (W)</td>
</tr>
<tr>
<td>Wave Height</td>
<td>The vertical distance between crest and trough of the wave</td>
</tr>
<tr>
<td>Wave Reflection</td>
<td>The reflection of some wave energy that is caused when the wave energy transitions from one medium to a denser medium.</td>
</tr>
<tr>
<td>Wave Shoaling</td>
<td>The effect by which surface waves entering shallower water increase in wave height (which is about twice the amplitude).</td>
</tr>
</tbody>
</table>

**Wave Shoaling**

In fluid dynamics, wave shoaling is the effect by which surface waves entering shallower water increase in wave height (which is about twice the amplitude). It is caused by the fact that the group velocity, which is also the wave-energy transport velocity, decreases with the reduction of water depth. Under stationary conditions, this decrease in transport speed must be compensated by an increase in energy density in order to maintain a constant energy flux. Shoaling waves will also exhibit a reduction in wavelength while the frequency remains constant. In shallow water and parallel depth contours, non-breaking waves will increase in wave height as the wave packet enters shallower water. This is particularly evident for tsunamis as they wax in height when approaching a coastline, with devastating results.

**Young's modulus**

Ym or E, is an indicator of the stiffness (elasticity) of a ceramic material. Ym is determined from the value for the stress applied to the material divided by the value for the resulting strain in the same direction.
3. Basic Wave Equations and Theory

The following pictures and formulas for basic ocean wave theory are taken from The Civil Engineering Handbook - Ch 36 “Coastal Engineering” as a reference for the reader. Wave formation, motion, and energy can be described as follows and viewed in Figure 12. – Wave Basics and basic formulas are called out in Table 3: Wave Formulas:

![Wave Basics Diagram](image)

\[ \eta = A \cos (\omega x - \omega t) \]
\[ \eta = A - H/2 \text{ at wave crest} \]
\[ \eta = -A - H/2 \text{ at wave trough} \]

Figure 18: Wave Basics
<table>
<thead>
<tr>
<th>Relative Depth</th>
<th>Shallow Water ( d/L &lt; 1/20 )</th>
<th>Transitional Water ( 1/20 &lt; d/L &lt; 1/2 )</th>
<th>Deep Water ( d/L &gt; 1/2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Wave profile</td>
<td>Same as “Transitional Water”</td>
<td>( \eta = \frac{H}{2} \cos \left[ 2k_0 (\alpha t - x) \right] = \frac{H}{2} \cos \theta )</td>
<td>Same as “Transitional Water”</td>
</tr>
<tr>
<td>2. Wave celerity</td>
<td>( C = \frac{L}{T} = \sqrt{gd} )</td>
<td>( C = \frac{L}{T} = \frac{\sqrt{T}}{2\pi} \tanh(kd) )</td>
<td>( C = C_0 = \frac{L}{T} = \frac{\sqrt{T}}{2\pi} )</td>
</tr>
<tr>
<td>3. Wavelength</td>
<td>( l = T \sqrt{gd} = C T )</td>
<td>( l = \frac{\sqrt{T}^2}{2\pi} \tanh(kd) )</td>
<td>( l = l_0 = \frac{\sqrt{T}^2}{2\pi} = C_0 T )</td>
</tr>
<tr>
<td>4. Group velocity</td>
<td>( C_g = \frac{C}{C} = \sqrt{gd} )</td>
<td>( C_g = nC = \frac{1}{2} \left( 1 + \frac{2kd}{\sinh[2kd]} \right) C )</td>
<td>( C_g = \frac{1}{2} C = \frac{\sqrt{T}}{4\pi} )</td>
</tr>
<tr>
<td>5. Water particle velocity</td>
<td>(a) Horizontal</td>
<td>( u = \frac{H}{2} \sqrt{g} \cos\theta )</td>
<td>( u = \frac{H}{2} \sqrt{g} \cosh \left( \frac{z + \xi}{2kd} \right) )</td>
</tr>
<tr>
<td></td>
<td>(b) Vertical</td>
<td>( w = \frac{H\pi}{T} \left( 1 + \frac{z}{d} \right) \sin\theta )</td>
<td>( w = \frac{H}{2} \sqrt{g} \frac{\cosh \left( \frac{z + \xi}{2kd} \right)}{\sinh kd} \sin\theta )</td>
</tr>
<tr>
<td></td>
<td>(a) Horizontal</td>
<td>( a_z = \frac{1}{T} \sqrt{g} \sin\theta )</td>
<td>( a_z = \frac{H}{2} \left( \frac{\cosh \left( \frac{z + \xi}{2kd} \right)}{\sinh kd} - \cos\theta \right) )</td>
</tr>
<tr>
<td></td>
<td>(b) Vertical</td>
<td>( \xi = -\frac{HT}{4\pi} \sqrt{g} \sin\theta )</td>
<td>( \xi = -\frac{H}{2} \frac{\cosh \left( \frac{z + \xi}{2kd} \right)}{\sinh kd} - \sin\theta )</td>
</tr>
<tr>
<td></td>
<td>(a) Horizontal</td>
<td>( \zeta = \frac{H}{2} \left( 1 + \frac{z}{d} \right) \cos\theta )</td>
<td>( \zeta = -\frac{H}{2} \frac{\cosh \left( \frac{z + \xi}{2kd} \right)}{\sinh kd} \cos\theta )</td>
</tr>
<tr>
<td></td>
<td>(b) Vertical</td>
<td>( \zeta = \frac{H}{2} \left( 1 + \frac{z}{d} \right) \cos\theta )</td>
<td>( \zeta = -\frac{H}{2} \frac{\cosh \left( \frac{z + \xi}{2kd} \right)}{\sinh kd} \cos\theta )</td>
</tr>
<tr>
<td>8. Subsurface pressure</td>
<td>( p = \rho g (\eta - z) )</td>
<td>( p = \rho g \frac{\cosh \left( \frac{z + \xi}{2kd} \right)}{\cosh kd} - \rho g \zeta )</td>
<td>( p = \rho g \frac{\cosh \left( \frac{z + \xi}{2kd} \right)}{\cosh kd} - \rho g \zeta )</td>
</tr>
</tbody>
</table>
4. Piezoelectric Energy Equations

The following constitutive relations were referenced from the *Piezoelectric Ceramics Characterization* by TL Jordan and Z. Qunaies. The authors discuss that one must account for the changes of strain and electrical displacement in three orthogonal directions caused by cross-coupling effects due to applied electrical and mechanical stresses:

- The state of strain is described by a second rank tensor $S_{ij}$, and the state of stress is also described by a second rank tensor $T_{kl}$.
- The relationships relating the stress tensor to the strain tensor, compliance $s_{ijkl}$, and stiffness $c_{ijkl}$, are fourth rank tensors.
- The relationship between the electric field $E_j$ (first rank tensor) and the electric displacement, $D_i$ (also a first rank tensor), is the permittivity $e_{ij}$, which is a second rank tensor.

The piezoelectric equations are therefore written as:

\begin{align*}
D_i &= e_{ij}^T E_j + d_{ijk} T_{jk} \\
S_{ij} &= d_{ijk} E_j + s_{ijkl} T_{kl}
\end{align*}

where $d_{ijk}$, $d_{ijk}$ are the piezoelectric constants (third rank tensor). Superscripts T and E denote that the dielectric constant $e_{ij}$ and the elastic constant $s_{ijkl}$ are measured under conditions of constant stress and constant electric field respectively.

Displacement of a piezo stack (rod) can be estimated by the following equations:[36]

\begin{align*}
\Delta L_{Z'} &= d_{33} n V_{Z'} \\
\Delta L_{X'} &= d_{31} n V_{X'}
\end{align*}

where:

- $\Delta L_{Z'} = \text{displacement \ [m]}$
- $d_{33} = \text{strain coefficient (field and displacement in polarization direction) \ [m/V]}$
- $d_{31} = \text{strain coefficient (field and displacement in non-polarized direction) \ [m/V]}$
- $n = \text{number of layers}$
- $V_{Z'}$ and $V_{X'} = \text{operating voltage (Volts) in the } Z' \text{ and } X' \text{ directions}$
5. Shallow Water Wave Data

See Excel Spreadsheets – To be printed out and inserted into paper report.

- Wave Data – Sphere Damper.xls
- Wave Data – Sphere Damper, Radius Equal to Min Depth.xls
- Wave Data – Sphere Damper, Min Radius for Acceptable FD.xls
- Wave Data – Cylinder Damper.xls
- Wave Data – Cylinder Damper Height Equal to Twice Max Hs.xls
- Wave Data – Cylinder Damper, Min Radius for Acceptable FD.xls
6. Other References

6.1. List of wave energy converters

Table 14 was referenced from “Floating Wave Dampers” by Schamhart\textsuperscript{40} and gives an overview multiple types of WECs currently in-use and being tested. The devices are split between the different conversion techniques and small pictures give an indication of their functioning.

These WECs are classified by these basic energy conversion principles:
A Heaving or pitching bodies
B Oscillating water column
C Pressure devices
D Surging-wave energy converters
E Particle motion converters
F Overtopping devices
<table>
<thead>
<tr>
<th>Category</th>
<th>Specific Energy Conversion Process</th>
<th>Device</th>
<th>Device Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Deadweight Buoy</td>
<td>21: OPT PowerBuoy</td>
<td>developed in the USA and Australia, prototype testing in Portland, Australia</td>
</tr>
<tr>
<td></td>
<td></td>
<td>22: Danish heaving buoy</td>
<td>developed in Denmark, prototype testing in Hanstholm</td>
</tr>
<tr>
<td></td>
<td>Phase-controlled power buoy</td>
<td></td>
<td>developed in Norway, prototype testing in the Trondheimsfjord, minimum water depth is 40m for a device diameter of 10m, pneumatic power take off</td>
</tr>
<tr>
<td></td>
<td>1: DELBUOY</td>
<td></td>
<td>developed in the U.S. to provide fresh water in remote areas by reverse osmosis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>22: Hosepump</td>
<td>developed in Sweden</td>
</tr>
<tr>
<td></td>
<td>1: Freely heaving float with inertial reaction point</td>
<td>1: Hosepump principle</td>
<td></td>
</tr>
<tr>
<td>category</td>
<td>specific energy conversion process</td>
<td>device</td>
<td>device information</td>
</tr>
<tr>
<td>----------</td>
<td>----------------------------------</td>
<td>--------</td>
<td>--------------------</td>
</tr>
<tr>
<td></td>
<td></td>
<td>IPS buoy</td>
<td>developed in Sweden, tested device had a diameter of 3m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>AquaBuoy</td>
<td>developed in Sweden and the USA based on the hosepump and the IPS buoy; minimum water depth is 50m, device diameter is 5m with a draught of 30m, part of the ESH EPRI assessment</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Contouring flow with inertial reaction point</td>
<td>developed in Ireland, prototype testing in the Shannon river estuary, designed for fresh water production by reverse osmosis for remote islands</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wave energy module</td>
<td>developed in the USA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Kaiyo jack-up rig</td>
<td>developed in Japan, prototype testing on Iriomote Island, Okinawa</td>
</tr>
<tr>
<td></td>
<td>Cockerell Contouring raft</td>
<td>developed in the UK</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hagen Contouring raft</td>
<td>developed in the USA</td>
<td></td>
</tr>
<tr>
<td>category</td>
<td>specific energy conversion process</td>
<td>device</td>
<td>device information</td>
</tr>
<tr>
<td>----------</td>
<td>-----------------------------------</td>
<td>--------</td>
<td>--------------------</td>
</tr>
<tr>
<td>A/B</td>
<td>Floating articulated cylinder with mutual force reaction</td>
<td><img src="image1.png" alt="Pelamis side view" /></td>
<td>developed in the UK, test site: Shetland/Isle of Lewis, designed for water depth 250m, device diameter 4.6m, total device length 160m part of the ESI EPRI assessment</td>
</tr>
<tr>
<td></td>
<td><img src="image2.png" alt="Pelamis top view" /></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>A floating vessel</td>
<td><img src="image3.png" alt="ConWEC" /></td>
<td>developed in Norway</td>
</tr>
<tr>
<td></td>
<td><img src="image4.png" alt="Freely floating OWC" /></td>
<td><img src="image5.png" alt="navigation buoy" /></td>
<td>developed in China based on Masuda navigation buoy, in operation at various sites</td>
</tr>
<tr>
<td></td>
<td><img src="image6.png" alt="查看详情" /></td>
<td><img src="image7.png" alt="Masuda navigation buoy" /></td>
<td>developed in Japan, in operation at various locations, device diameter of 3m with a draught of 3.75m</td>
</tr>
<tr>
<td></td>
<td><img src="image8.png" alt="查看详情" /></td>
<td><img src="image9.png" alt="Kaimi floating platform" /></td>
<td>developed in Japan, prototype test site: Yura</td>
</tr>
<tr>
<td>category</td>
<td>specific energy conversion process</td>
<td>device</td>
<td>device information</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>------------------------------------</td>
<td>--------</td>
<td>-----------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Fixed floating OWC</td>
<td>(23) Mighty Whale</td>
<td></td>
<td>developed in Japan, tested in Guinahbo bay, minimum water depth of 40m, device is 10m wide and 10m long.</td>
</tr>
<tr>
<td></td>
<td>[I] Sparrow</td>
<td></td>
<td>developed in the UK, prototype tested in Plymouth</td>
</tr>
<tr>
<td></td>
<td>[I] Shim</td>
<td>wind-wave system</td>
<td>developed in South Korea</td>
</tr>
<tr>
<td></td>
<td>[I] Bottom-mounted OWC</td>
<td>(1) Osprey</td>
<td>developed in UK, test site in Thurac</td>
</tr>
<tr>
<td>Submerged pulsating volume body with suction point</td>
<td>(1) Archimedes wave swing</td>
<td></td>
<td>developed in the Netherlands, full scale prototype testing at Viano do Castello, Portugal, minimum water depth is 30m, device diameter is 9.5m, part of the EWI EPHI assessment</td>
</tr>
</tbody>
</table>
6.2. Selected Rubber Materials for Shallow Wave Device

Table 15: Selected Rubber Materials for Shallow Wave Device

<table>
<thead>
<tr>
<th>Name:</th>
<th>Young’s modulus (MPa)</th>
<th>Tensile strength (MPa)</th>
<th>Elongation (%)</th>
<th>Thermal expansion (10^-6/K)</th>
<th>Thermal conductivity (W/m.K)</th>
<th>Glass transition temperature (°C)</th>
<th>Service temperature (°C)</th>
<th>Density (kg/m³)</th>
<th>Resistivity (Ohm.m)</th>
<th>Dielectric loss factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butadiene Rubber</td>
<td>NA</td>
<td>10-15</td>
<td>200-400</td>
<td>6.5-6.6</td>
<td>0.25</td>
<td>-100 to -50</td>
<td>70 to 70</td>
<td>900 to 1000</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Etheneprop enediene Rubber</td>
<td>2-10</td>
<td>10-20</td>
<td>250-500</td>
<td>NA</td>
<td>0.26-0.26</td>
<td>-55</td>
<td>-40 to -65</td>
<td>860</td>
<td>1e+21 - 1e+21</td>
<td>0.0005 - 0.001</td>
</tr>
<tr>
<td>Natural Rubber</td>
<td>1-5</td>
<td>20-30</td>
<td>850</td>
<td>6.7</td>
<td>0.13</td>
<td>0.42</td>
<td>-70</td>
<td>910 to 930</td>
<td>1e+21 - 1e+21</td>
<td>0.0016 - 0.005</td>
</tr>
<tr>
<td>Styrenebutadiene Rubber</td>
<td>2-10</td>
<td>10-25</td>
<td>250-700</td>
<td>6.7</td>
<td>0.2-0.25</td>
<td>-65 to -50</td>
<td>-30 to 70</td>
<td>940</td>
<td>1e+19 - 1e+20</td>
<td>0.01 - 0.03</td>
</tr>
<tr>
<td>Nitrile Rubber</td>
<td>2-5</td>
<td>10-20</td>
<td>200-500</td>
<td>NA</td>
<td>NA</td>
<td>-35 to -110</td>
<td>1000</td>
<td>1e+14 - 1e+15</td>
<td>0.05 - 0.05</td>
<td></td>
</tr>
</tbody>
</table>

Technical general purpose rubber as 1,4-polymerisation product of polybutadiene with dominating cis-configuration. Production assumed to be equal to polybutadiene in general as produced throughout Europe. The strength, heat buildup, and wear resistance is improved by the addition of 25% carbon black. Butadiene rubber is almost exclusively applied as a necessary component of rubbers for tires. Enhances strongly the wear resistance.

Production of 1 kg product including mixing and vulcanization. Flexible, weather-resistant.

Incineration 45,2 MJ/kg. Moderate injection mouldability.

Copolymer of Styrene and Butadiene in a 23/77% ratio mixture reinforced with 30% carbon black. Average data from the European industry. Copolymerization data assumed equal to the polymerization process of the components. Oxidation-, water-, acid- and lye-resistant. Poor resistance against organic solvents and mineral oil.

Copolymer of Acrylonitrile and Butadiene in a 30/70% ratio mixture. Average data from the European industry. Copolymerization data assumed equal to the polymerization process of the components. Permeability for gases is poor. Oil resistant. This rubber is most applied (90%) of all rubbers. Very good resistance against oil and other organics.
### 6.3. Table of Sample Piezoelectric Materials and Properties

#### Table 16: Table of Sample Piezoelectric Materials and Properties

<table>
<thead>
<tr>
<th>Piezoelectric Properties of Materials</th>
<th>density</th>
<th>Effective elastic constant</th>
<th>piezoelectric constant</th>
<th>permitivity</th>
<th>Stress Limits</th>
<th>Tensile Modulus</th>
<th>Poisson's ratio</th>
<th>Young's modulus - E1</th>
<th>E2</th>
<th>Ultimate Stress</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>PZT 8060 kg/m^3</td>
<td>C33</td>
<td>k31</td>
<td>k33</td>
<td>d31</td>
<td>d33</td>
<td>ε33 or dielectric constant (ε33/ε0)</td>
<td>14.3 NF/m 800</td>
<td>3.6 N tension , 11.8 N compression 51.3 MPa</td>
<td>62.3 GPa</td>
<td>0.33 GPa</td>
<td>63 N/m^2</td>
</tr>
<tr>
<td>PIC 255 7.80 g/cm^3</td>
<td>82 GP a</td>
<td>0.35</td>
<td>0.69</td>
<td>-180 m^3/10^12 m/V</td>
<td>550 10^-12 m/V</td>
<td>1750</td>
<td>3300</td>
<td>5.1 10^-10 N/m^2</td>
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<tr>
<td>AP 855 7.7 g/cm^3</td>
<td>0.4*1</td>
<td>0.76</td>
<td>276 10^-12 m/V</td>
<td>630 10^-12 m/V</td>
<td>3300</td>
<td>3400 E0 = 8.854 pF/m E33 = 25.55 nF/m</td>
<td>62 62</td>
<td>200 MPa</td>
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</tr>
<tr>
<td>PZT -5H 7500 kg/m^3</td>
<td>-320 (10^-12 m/V)</td>
<td>3400 E0 = 8.854 pF/m E33 = 25.55 nF/m</td>
<td>62 62</td>
<td>200 MPa</td>
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