Chapter 3 Ocean Energy Resource

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3.1 Introduction

From the oceans we can harvest: **thermal energy**, from the temperature difference of the warm surface waters and the cool deeper waters, as well as **potential** and **kynetic** energy, usually lumped as **mechanical energy**, from the tides, waves and currents.

The technological concept to harvest the thermal energy in the ocean is universally called Ocean Thermal Energy Conversion (OTEC). The basic electric generation systems are: *closed-cycle, open-cycle,* and *hybrid.* These will be discussed in detail in the "Available commercial and prototype conversion technology" of this report.

Oceans mechanical energy is very different from the oceans thermal energy. Tides are driven primarily by the gravitational pull of the moon, waves are driven primarily by the winds and ocean currents are even more complex driven by solar heating and wind in the waters near the equator, also by tides, salinity and density of the water. For these reasons tides, waves and currents are intermittent sources of energy, while ocean thermal energy is quite constant. The electricity conversion of all three usually involves mechanical devices.

This Ocean Energy Resource section is organized in terms of the energy resource. We will discuss in order; tides, currents, thermal and waves. The physical source of each resource is discussed as well as the resource availability and variability to produce electricity. The available technology to produce electricity is described and costs are included as available.

3.2 Tides

The interaction of the sun-moon-earth system causes ones of the strangest phenomena: *tides*. Tides rise and fall is the product of the gravitational and centrifugal forces, of primarily the moon with the earth. The gravitational forces maintain the moon on its positions with respect to the earth, forcing to pull the earth and the moon together see Figure 3.1. The centrifugal force acts on the opposite direction pulling the moon away from the earth. These two forces act together to maintain the equilibrium between these two masses.

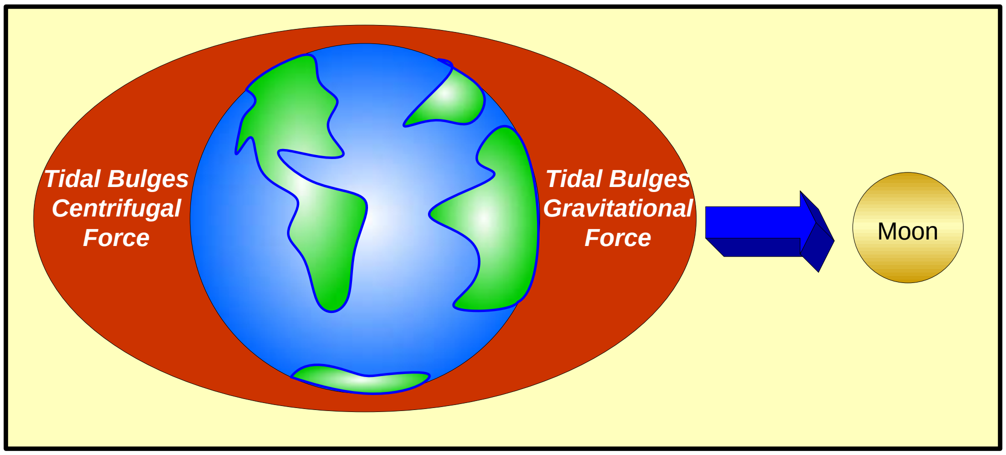

Figure 3.1 Tidal Bulges due to the Gravity and Centrifugal Forces

The influence of the sun can be included on the balance of the entire system. The distance plays an important role on the development of the tides. Based on the Newton's laws, the gravitational force is proportional to the square of the distance of two bodies, but the tidal force is proportional to the cube of the distance. For this reason although the moon has a much smaller mass than the sun it is much closer to the earth. The moon effect is 2¼ greater than that of the sun on the generation of tides [O1].

The gravitational force of attraction of the moon causes that the oceans waters bulge on the side of the earth that faces the moon. The centrifugal force produce the same effect but in the opposite side of the earth. On these two sides it can be observe the maximum amplitudes of the tides (high tides) and on the midways of it occur the minimum amplitudes of the tides (low tides). As the earth rotates these two bulges travel at the same rate as the earth's rotation. The moon rotates around the earth with respect to the sun approximately 29.5 days (lunar month) in the same direction that the earth rotates every 24 hours [O2]. The rotation of the earth with respect to the moon is approximately 24.84 hours (24 hours and 50 minutes) and is called lunar day. This is the reason of why the tides advance approximately 50 minutes each day [O2].

In the same manner that the ocean waters bulges towards the moon, the gravitational force of the sun causes that the ocean waters bulges too but in a lesser degree. Twice a month, when the earth, the moon and the sun are aligned (full and new moon) the tide generating forces of the sun and the moon are combined to produce tide ranges that are greater than average knowing as the *spring tides* [O3]*.* At half moon (first and third quarters) the sun and the moon are 90º with respect to the earth and the tide generating forces tend to produce tidal ranges that are less than the averages knowing as the *neap tides*, see Figure 3.2 [O3]*.* Typically the spring tides ranges tend to be twice of the neap tides ranges.

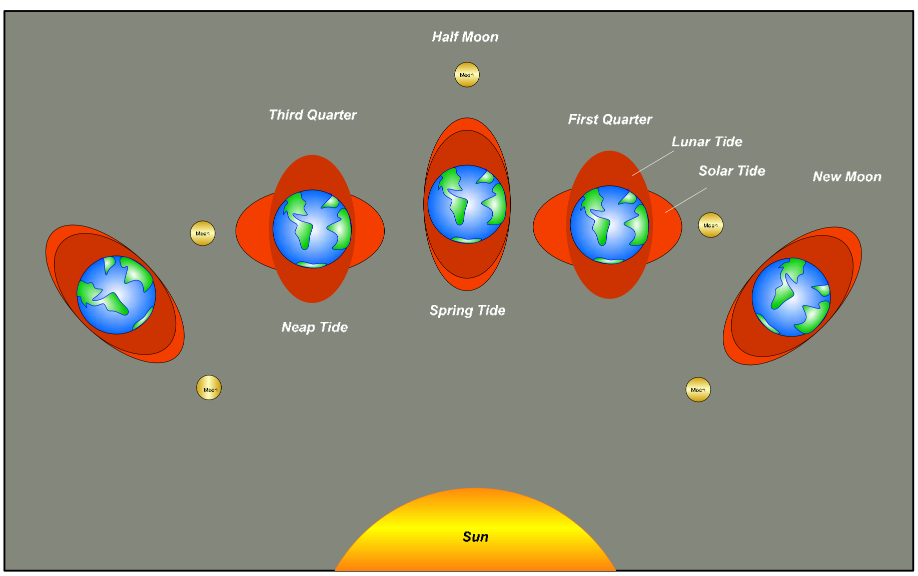

Figure 3.2 Neap and Spring Tides

The tidal movements can be reflect and restrict by the interruption of masses of land, the bottom friction can reduce its velocity and the depth, size and shape of the ocean basins, bays and estuaries altered the movements of the tidal bulges and generate different types of tides [O1]. There are three types of tides: diurnal, semidiurnal and mixed, see Figure 3.3 [O4].

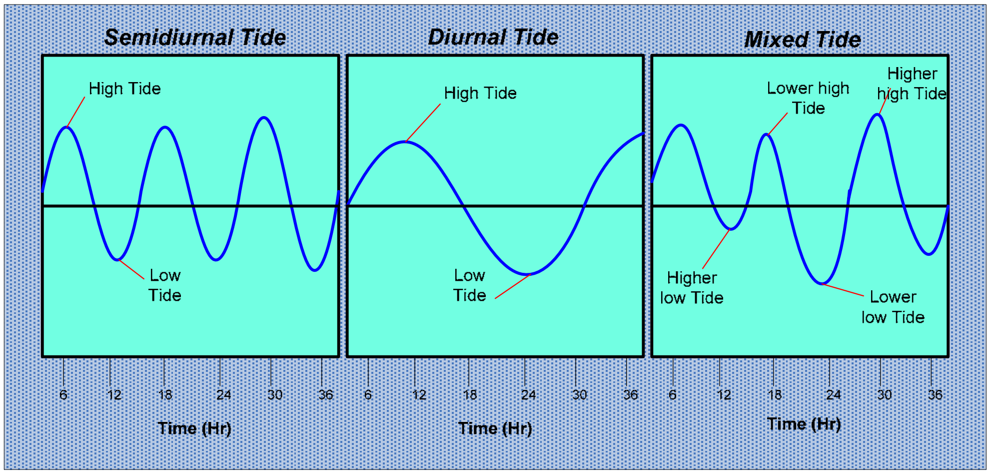

Figure 3.3 Types of Tides

Diurnal tides (daily) present one single high and low water during a period of a lunar day of 24 hours and 50 minutes and occur in the Gulf of Mexico, Southeast Asia and the coast of Korea, *semidiurnal tides* (twice a day) present two high and two low waters during a lunar day with periods of 12 hours and 25 minutes and is common along the Atlantic coast of North America and the *mixed tides* that presents two unequal high and two unequal lows waters and generally have periods of 12 hours and 25 minutes. In a lunar month this type of tide that is common on the Pacific Ocean coast of the United States can experience semidiurnal and diurnal tides characteristics. In 1964 Davis classified the tidal ranges as: *microtidal* with tidal range less than 2 meters, *mesotidal* with tidal range between 2 and 4 meters and *macrotidal* with tidal range of more than 4 meters [O5].

3.2.1 Tidal Energy to Electric Energy Conversion

The technology that is use to produce electricity using the difference between the low and high tides is very similar to the one use on the generation of electricity on the traditional hydroelectric power plants. The use of the tidal energy requires a dam or barrage across a shallow area preferably an estuary, bay or gulf of high tidal range where the difference on the low and high tide have to be at least 5 meters [O1]. The tide basins are filled and empty every day with the flood tides when the water level rises and with the ebb tides when the water level falls. On the barrage there are low-head turbines and sluices gates that allow the water to flow from one side of the barrage to inside the tidal basin. This difference on elevation of the water level creates a hydrostatic head that generates electricity. There are different modes to generate electricity using the barrage systems:

Ebb generation - Incoming water (flood tide) is allowed to flow freely to fill the basin until high tide, then the sluices are close and water are retained on one side of the barrage. When the level of the water outside of the barrage decreased (ebb tide) sufficiently to create a hydrostatic head between the open waters and the tide basin, the sluices are open and water flows through the turbines and generate electricity. Once the head is low the sluices gates are open and the basin is filled again [O6].

Flood generation - During the flood tide the sluices gates and low-head turbines are kept closed to allow the water level outside of the barrage to increase. Once a hydrostatic head is created the sluices gates are opened and the water flows through the turbines into the basin. This mode is less efficient than the ebb mode [O1, O6].

Two way generation - This mode permits to generate electricity using both the ebb and the flood tide. The main problem with this type of mode is that the turbines must work both ways, when water enters or exits the basin. This requires more expensive turbines and at this time computer simulations do not indicate that this mode increases significantly the energy production.

Pumping- On the ebb generation the hydrostatic head can be increased reversing the power and turning the turbine-generator into a pump-motor. During the generation the energy that was use is returned.

Double basin- All of the modes discuss above use one tide basin. Using two basins, the turbines are placed between the basins. The main basin will going to use the ebb generation mode to operate and pump water with part of the energy that is generated to and from the second basin to generated electricity continuously. This mode has the disadvantage that is very expensive.

3.2.2 Tidal Power around the World

Worldwide there are places that have large tidal ranges. Some of these places are The Bay of Fundy Canada with a mean tidal range of 10 m, Severn Estuary between England and Wales with a mean range of 8 m and the northern of France with a mean range of 7 m.

The first large-scaled tide generation plant is located in Brittany on the La Rance River on France. It was completed in 1966 at a cost of $100 millions. The generation plant has a capacity of 240 MW. The plant consists of 24 bulb-type turbine generators of 5.35 m (17.55 ft.) diameter with 4 mobile pales and a rated capacity of 10 MW. The barrage has a length of 910 m (2986 ft.) and serves as a four-lane highway that connects Saint Malo and Dinard. The bulb turbines were design to operate on ebb or flood generation mode and pump water either into or out of the basin when there are slack tides periods. These turbines have the disadvantage that the water flows around them and make the maintenance difficult and expensive. The plant is operated almost of the time on the ebb generation mode because operate on the two-way generation mode (ebb and flood tides) was prove not to be successful. Only when high spring tides are present the plant operates on two-way generation mode. The plant average generation was about 64 GW per year (0.012% France energy consumption). On 1996 the plant passes to a 10 year refurbishment plan for its 24 bulb turbines.

On Annapolis Royal in Nova Scotia, Canada there is a 20 MW pilot tidal power plant since 1984. This plant operates using a rim-type generator with the large Straflo turbine in the world. It produces approximately 3 GW per year. This turbine generates electricity only on one direction (unsuitable to pump), but can be place on the barrage making the maintenance more simple.

A small pilot tidal power plant was constructed on Kislogubskaia near Murmansk, Russia. It was completed on 1968 with a capacity of 400 kW. This plant used a reversible hydraulic turbine that was coupled to a synchronous generator.

Other places around the world are suitable for the development of tidal power plants because their favorable tidal ranges. Some possible sites for the development of barrage tidal power plants are shown in Table 3.1

Table 3.1 Possible Sites for the Development of Tidal Power Plants

Site	Mean Tidal Range (m)	Barrage length (m)	Estimated annual power production (GWh)
Severn Estuary (UK)	8.0	17000	12900
Solway Firth (UK)	5.5	30000	10050
Bay of Fundy (Canada)	10	8000	11700
Gulf of Khambnat (India)	6.1	25000	16400

Economical and environmental aspects are some of the constraints that these tidal power plants have to surpass to reach a development on a near future.

3.2.3 Advantages and disadvantages of Tidal Power

Using a barrage to generate electricity using tides offers some advantages. The use of tides instead of fossil fuel to generate electricity reduced the greenhouse effects, improving the conditions of the environment. In La Rance tidal power plant as example on the top of the barrage there is a four-lane highway that cuts 35 km of distance between the towns of Saint Malo and Dinard representing an improvement on the traffic.

A disadvantage on the tidal power plants is the availability of the tidal power. The tides are linked to the lunar than to the solar cycle, this make that the ranges varied with annual and semiannual components as well with the spring and neap tides. The high tides ranges are present in a period of five to six hours after the high tide cycle. Because this cycle moves 50 minutes each day not always the high tides ranges coincide with the peak demand hours of electricity.

The high cost that represents the construction of the barrage and the fact that the selected sites need to have specific characteristics, like a large basin area with a narrow entrance to reduce the size of the barrage add restrictions to the development of it.
The experience with the La Rance barrage on France proves that the resource is available and almost infinite. The uses of small-scale barrage systems are a possibility that is taken into consideration to reduce some of the economic and geographic problems that encounters the tidal power generation plants.

3.2.4 Available Tidal Power in Puerto Rico

The tides behavior along the island of Puerto Rico is complex and variable. Along the north and west coast of the island the tides are principally semidiurnal (occur twice a day) but can present mixed tides characteristics too [O7]. On the south and east coast including Vieques the tides behavior is totally different from the north and west coast; the tides are principally diurnal (once a day) but can experience periods of mixed tides [O7]. This occurs because the diurnal band that is on the south is surrounded by a strong semidiurnal tide.

To predict the tidal coastal elevation NOAA had tidal stations. These stations known as *reference stations* are located at Magueyes Island at Lajas and at San Juan [O8]. The other stations such as the Arroyo, Guánica, Mayaguez, Ponce, Culebra, Vieques, Maunabo and Roosevelt Roads are known as subordinate stations. The predictions on subordinate stations are made with comparisons of simultaneous tide observations at these stations and its reference station. With the application of time differences and height ratios the approximations are very accurate but not as accurate as the one made on the reference stations because these are based on larger periods of analysis.

In Puerto Rico and along all the Caribbean tides have small ranges that can be classified as microtidal, less than 2 meters. The mean high water level is + 1.0 ft. above mean lower low water (MLLW) and the extreme low water level at - 1.0 ft. at MLLW. Table 3.2 shows some of the maximum mean tide level (mean of low and high tide), measure in feet, and reference to the mean lower low water (MLLW) of the different NOAA stations around Puerto Rico [O8].

Table 3.2 Maximum mean tide level in feet [O8]

Station	*Maximum mean tide level (ft.)*
*Arroyo	1.1
*Culebra	1.6
*Guanica	1.0
*Maunabo	1.0
*Ponce	1.1
*Vieques	1.1
Magueyes Island	1.0
**Mayaguez	1.8
**Roosevelt Roads	1.2
San Juan	1.9

* Reference to the Magueyes Island Reference Station

**Reference to the San Juan Reference Station

3.2.5 Conclusion on Available Tidal Power for Puerto Rico

To consider a site for the economic development of a tidal power plant the difference between the low and high tidal range has to be at least 5 meters to create the hydrostatic head that generate electricity. The site needs to have a large basin with a narrow entrance to reduce the cost of the construction of the barrage. Unfortunately, in Puerto Rico the differences between low and high tides are under 1 meter and the few sites that can qualify are under use for maritime transportation, natural reserves (Jobos Bay National Estuary Research Reserve) and for recreational and tourism purposes.

3.3 Ocean Currents

Ocean currents are driven by solar heating and wind in the waters near the equator, also by tides, salinity and density of the water. Current can be divided in two types: marine currents and tidal currents. Marine currents are relatively constant and flow in one direction. Tidal currents occurred close to the shore due to gravitational forces. There are several important currents close to the United States like the Gulf Stream, Florida Straits Current, and the California Current [O9].

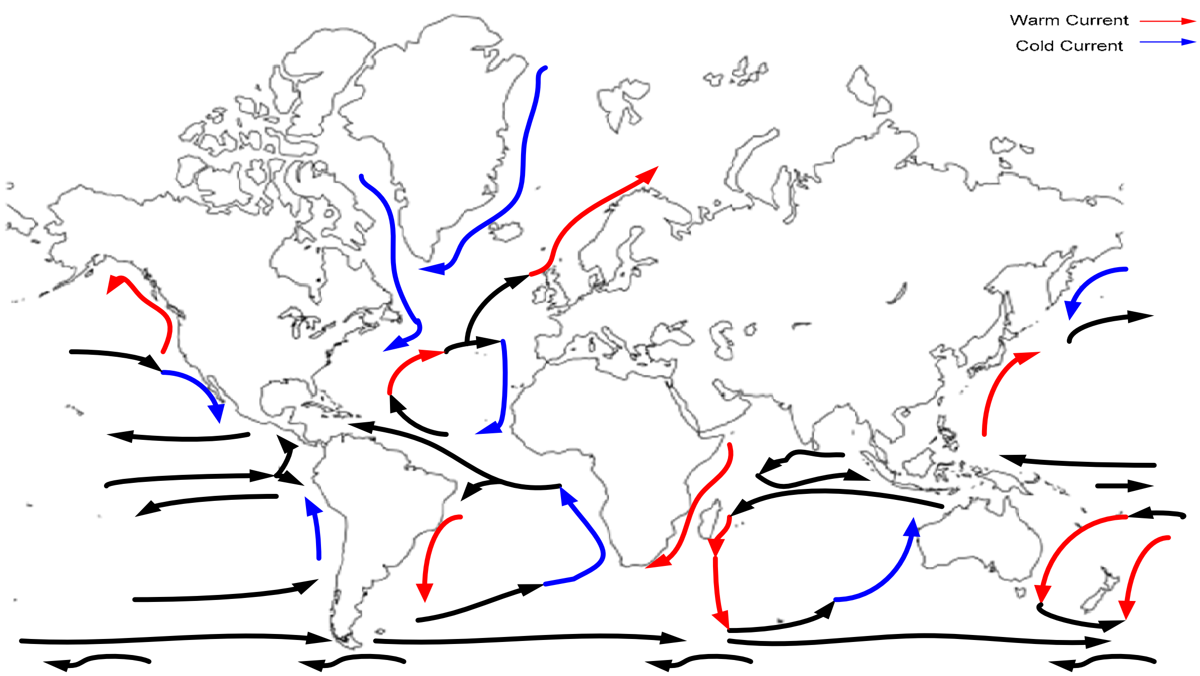

Figure 3.4 Map of distribution of ocean currents through the world [O10].

Currents are flowing bodies like wind. Current energy can be calculated using the formula of kinetic energy of flowing bodies, $KE = 0.5 * \rho * V^3$. The kinetic energy of flowing bodies is proportional to the cube of their velocities and their density [O11]. Ocean energy can be compared with wind energy because these two types of resources are two forms of flowing bodies. The speed of ocean currents is lower when compared to wind speeds but the water is 832 times denser than air. Also ocean currents can be predicted with years in advanced as these depend of the movements of the sun and moon.

Through the world there can be found ocean currents of more than five knots or 2.5m/s (1 knot=0.50 m/s) and current energy has been estimated greater than 5,000 GW, with power densities of up to 15 kW/m^2.

The amount of power that can be extracted from a flowing mass depends on the interaction between the device used to extract the energy and the flowing mass [3] as shown in the following rearrangement of the formula for the kinetic energy available in the flowing mass:

$$\left(\frac{P}{A}\right)_{Water} = \frac{1}{2}\rho V^3$$

The power flux available to us from ocean currents depends of the cross-sectional area of the flow intercepted by the device **A** (in square meters). Also it depends of **ρ**, the water density (in kilograms per cubic meter; 1,000 kg/m3 for freshwater and 1,025 kg/m3 for seawater) and **V** is the current speed (meters per second). The dominant factor, as in the case of wind, is the current speed. Table 3.3 shows power densities for different current speeds.

Table 3.3 Power Density at Several Current Speeds

Current Speed (m/s)	Power Density (kW/m²)
0.5	64
1.0	513
1.5	1730
2.0	4100
2.5	8008
3.0	13836
3.5	21973
4.0	32800
4.5	46702
5.0	64063
5.5	85267
6.0	110700
6.5	140745
7.0	175788

3.3.1 Currents Energy to Electric Energy Conversion

Technologies to convert ocean currents energy into electricity are under development. Several devices are being tested and are very similar to wind energy technologies, consisting in turbines of horizontal and vertical axis of rotation used underwater. The purpose of these technologies is to capture the ocean currents generated by the flow created by the motion of tides [O9]. In the horizontal axis turbines the rotational axis is parallel to the directional of the water flow. In vertical axis systems the rotational axis turbines rotate perpendicular to the water flow [O12]. Table 3.4 and Table 3.5 present the different technologies available to extract ocean current energies, specifically those currents created by tides. In these tables [O12, O13, O14] it can be seeing the main characteristics of these turbines including a brief description, dimension, rated power, some information of costs, cut-in speed and foundation.

Table 3.4 Energy Conversion Devices (1) [O9, O12, O13, O14]

OCEAN CURRENTS ENERGY TECHNOLOGIES				
Company	GCK	Lunar Energy	Sea Gen	Open Hydro (Florida Hydro)
Turbine Name	Gorlov Helical Turbine	Rotech Tidal Turbine	Marine Current Turbines	Open Center Turbine
Description	Self-stating cross-flow turbine that can rotate twice the speed of water flow	Horizontal axis turbine	Twin open-axial flow rotors (propeller type)	Consist of an inner single- piece rotating disc
Dimensions	1m diameter, 2.5m length	105 ft height, 100 ft long	Rotor Diameter: 18m	Twin 15m diameter open-center turbine
Rated Power	1.5kW@1.5m/s 180kW@7.72m/s	Full scale prototype: 1MW RTT 2000 commercial unit: 2MW@6knots	2.5MW @3m/s	1520kW@5 knots (2.57m/s) water speed
Cut in Speed	0.5m/s but due to efficiency not recommended for velocities below 1.5m/s	1m/s	0.70m/s	0.70m/s
Output Power	110V, 60Hz AC	11kV AC 50-60Hz 3 phase	Variable frequency, 600V to be transformed to 11kV, 50 Hz	11kV, 50-60hZ, 3 phase
Foundation/Mooring	Suspended of barge or attached to sea bottom	Gravity Base	Monopile embeded in the sea bed	Bottom mounted steel gravity base
Weight	200 lbs.	2500 tons		
Depth	Waters as shallow of 4 m	30 feet	< 30m	
Cost	$6000 in quantities of five or less	Capital Cost: $1360-$1700/kW	Estimates of manufacturing costs for small projects: $2500/kW Larger projects: $1400-$1600/kW	

Table 3.5 Energy Conversion Devices (2) [O9, O12, O13, O14]

OCEAN CURRENTS ENERGY TECHNOLOGIES			
Company	Seapower Inc.	Verdant Power	
Turbine Name	EXIM Tidal Turbine Power Plant	Verdant Kinetic Hydro Power Systems	Underwater Electric Kite
Description	Based in a Savonius Turbine (S-shaped vertical axis turbine)	Three bladed axial-flow turbine	Twin horizontal axis turbine
Dimensions	Dual vertical axis rotor of 1m diameter and 3 m high	Rotor diameter of 5m	Turbine diameter of 4m and hub diameter of 0.5m
Rated Power	44kW@2.4m/s 60kW@5m/s	35.9kW@2.2m/s	400kW@3m/s(5.8knots)
Cut in Speed	1-2.5m/s	0.70m/s	1.54m/s
Output Power	400V AC, 50-60 Hz, 3 phase	35.9kW@2.2m/s	
Foundation/Mooring	Four anchors and chains	Turbine fixed to a reinforced pile that has been drilled and grounded into the rock bottom.	Slack moored
Weight		8000 lbs.	2.6-3.5 metric tons
Depth			
Cost		Production cost of $100000 per 35.9kW turbine	$1100-$1300/kW for sites of 3MW or larger

3.3.2 Ocean currents resource in Puerto Rico

The oceans around Puerto Rico have no named current systems in its vicinity. The closer system is the Caribbean Current that flows south of the island [O16]. Tidal currents are the superimposed component of the offshore currents.

Currents in Puerto Rico can be divided in [O15]:

- North and West: mixed and semidiurnal
- South: mixed and diurnal

The currents' data analyzed was taken with an ADCP (Acoustic Doppler Current Profiler). This data was taken at two different places of the Mayaguez coast and the Culebra coast. The currents with greater velocity were found at the west coast of Puerto Rico, more specifically at Mayaguez coast in a place known as Bajo de Sico. These currents move mostly in the northern direction. At this place the greater peak currents seen were close to 50 cm/s in the northern direction approximately 1 knot of speed with mean speeds of 20 cm/s. South of the Bajo de Sico another ADCP is installed which reflects peak currents of approximately 35 cm/s and mean speeds of 15 cm/s. At the Culebra coast the data reflect mean speeds of 10 cm/s [O15]. During Hurricane George in September 22, 1998 the greater currents register in the Mona Passage were of 150 cm/s at a depth of 34 m [O16].

3.3.3 Conclusion on Available Currents Power for Puerto Rico

As we has seen in this report ocean currents energy is one of the solutions for the incrementing energy demand of the world and the environmental impact as the result of using fossil fuels to generate electricity. Although we had seeing several devices that extract ocean current energy, most of them are in the prototype stage with plans to prove this prototypes in the sea of different parts of the world. Also, in the specifications of these devices we can see the cut-in speeds needed for them to begin operation and work efficiently. The lower cut-in speed is of 0.5 m/s for the Gorlov Helical Turbine but is not recommended due to efficiency problems. As it is discussed in the Puerto Rico current resource section peak currents that occur near the coast of the island are of the order of 0.5 m/s (approximately 1 knot). Currents speeds of 1.50 m/s had been seeing only during tropical storm events.

These peak currents do not fulfill the cut-in speed for the energy conversion devices, so we conclude that the extraction of this energy is not viable for Puerto Rico. It is recommended that as time pass and these devices are improved in aspects as energy extraction, cut-in speeds and efficiency, ocean current energy in Puerto Rico can be study again to be used for small application near the coast as a form to lighten the energy load.

3.4 Ocean Thermal Energy

The large difference between the temperatures of the ocean surface waters, especially on the tropics and the deep seawaters stimulate the presence of thermal gradients. Based on this concept, the Ocean Thermal Energy Conversion (OTEC) has been proposed and is currently under development. OTEC converts the difference between warm surface waters and cold deeper waters (approximately 1000 m below the surface) into energy. The minimum water temperature difference must be 20º C (36º F) to operate the OTEC power cycle on a satisfactory way.

This resource as others is concentrated on certain zones. These zones are located on the equatorial waters between the 10º N and 10º S except for the west coast of South Africa and in the tropical regions of 20º N and 20º S except of the for the west coasts of South America and Southern Africa [O17]. On this zone industrial nations such as the United States and Australia are located as well as approximately 29 territories and 66 developing nations [O18].

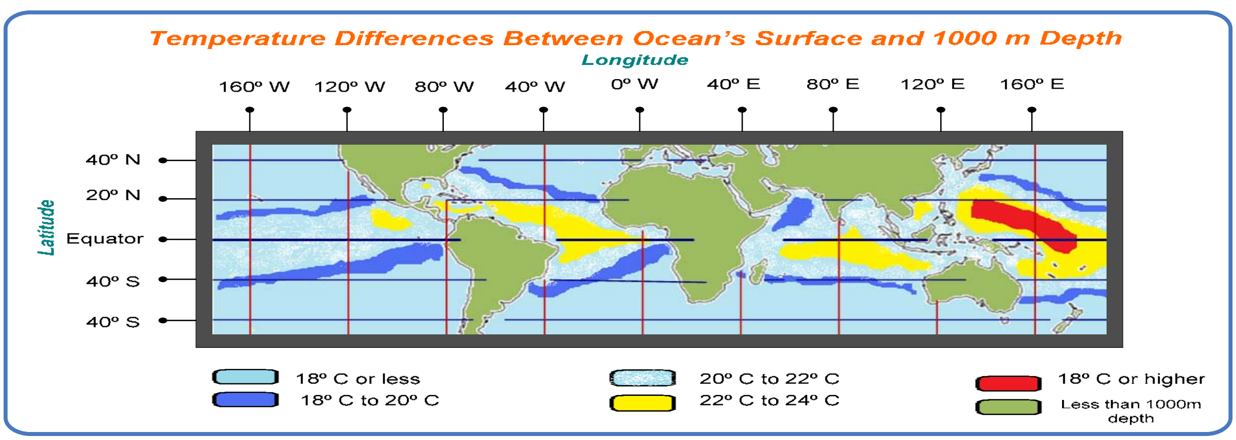

Figure 3.5 Ocean's Temperature Differences around the World [O18]

The concept of using the difference on temperatures on ocean waters is not a new one. In 1870 with the publication of "Twenty Thousands Leagues under the Sea" Jules Verne mentioned the use of the thermal gradient of the sea to produce electricity [O17]. It was until 1881 that a French physicist, Arsene d'Arsonval proposed the use of warm waters to vaporized ammonia to drive a turbine generator and condensed the ammonia using deep cold waters from 800 m to 1000 m of depth [O19]. This concept is known as the OTEC Close Circle. The OTEC Close Circle was proven in 1979, in Hawaii, when a small OTEC plant produced 50 kW of power.

In 1930 a French engineer, Georges Claude a student and friend of d'Arsonval, proposed the use of the seawater as the working fluid. This cycle is known as the OTEC Open Cycle and not only produces electricity but desalinated water too. On 1930 on the coast of Matanzas Bay, Cuba, Claude proved his concept. The power plant was installed on a ship and produced 22 kW with an ocean water temperature difference of only 14ºC [O19]. The operation of the plant ended the same year with a failure in the cold water intake pipe. In 1935, Claude built another power plant, on another ship of the coast of Brazil but failed in the installation of the vertical pipe that brings the cold water to the surface. He abandoned the project the same year.

3.4.1 Ocean Thermal Energy Conversion (OTEC)

OTEC offers the advantage of a resource which is available almost equally during the day and night with slightly variations on winter and summer. This renewable source can be combined with other applications that are deriving from it like: mar culture, potable water production and air conditioning refrigerant among others.

OTEC power plants must be located on areas where the ocean water temperature difference of at least 20º C can be accomplished. But other factors have to taking into account before considered a particular location suitable for an OTEC development. Some of these factors are [O20]:

- Distance from the thermal resource to the shore (grid interconnection),

- Depth of the cold water location and sea bottom,
- Type of OTEC facility (Shoreline or near-shoreline, platforms or free-floating),
- Oceans conditions (waves, currents),
- Sea bottom conditions (mooring, floating power conductors installations),
- Environmental Impacts
- Deep Ocean Water Applications (DOWA) potential,
- Government's incentives, and others.

To operate an OTEC plant to generate electricity two working cycles can be used: the OTEC closed cycle proposed by Arsene d'Arsonval and the OTEC open cycle proposed by Georges Claude.

3.4.1.1 OTEC working cycles

Open Cycle - In the open cycle warm seawater can be use as the working fluid. When the surface seawater is flashed evaporated it is pumped into a vacuum chamber to produce a spray of the liquid. Making the pressure of the chamber less than the saturation pressure of the spray of the water, it starts to boil. The steam that is produce passes through the turbine to generate electricity. The steam later condensates using the cold seawater and is not returned to the evaporator. This condensation process can be done using two methods: spray cold seawater over the steam or in a surface condenser in which the steam and the coldwater do not enter in contact with each other, producing desalinated water. If the condensation is done using the spray method the mixed of steam and cold water is discharged back to the ocean, see Figure 3.6.

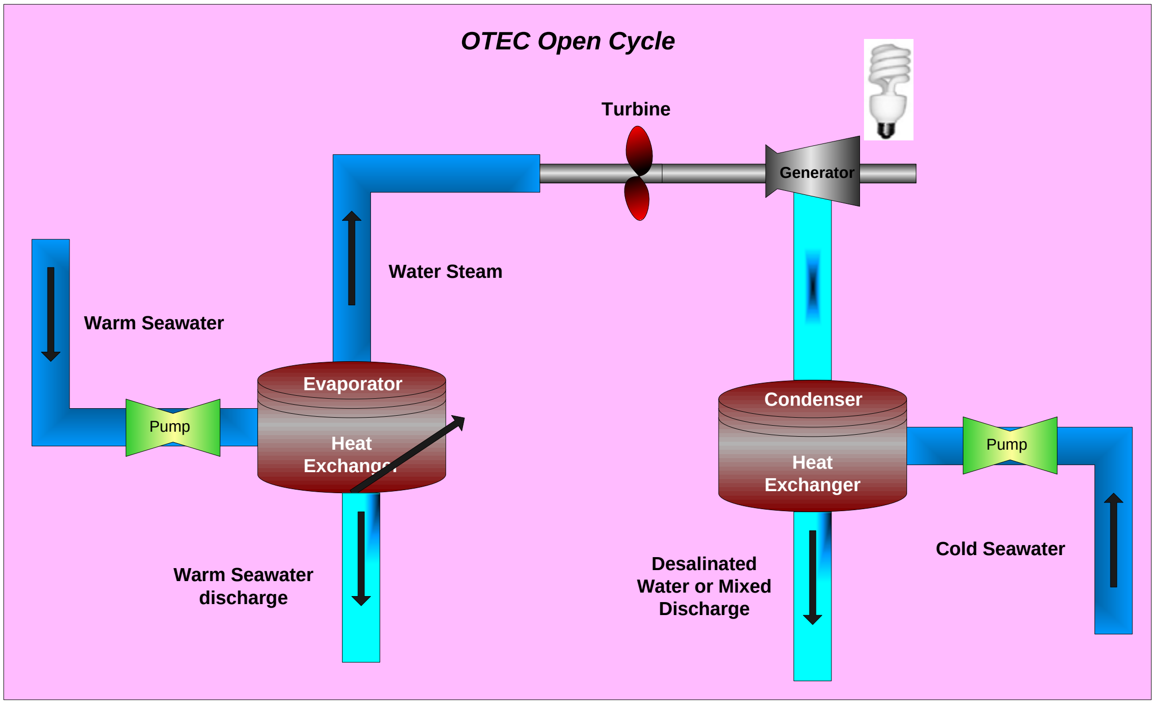

Figure 3.6 Simplified Diagram of the OTEC Open Cycle Process

Closed Cycle - In the OTEC closed cycle two working fluids work to complete the cycle. First, it is necessary to use warm seawater to vaporize a second working fluid such as ammonia, propane or a Freon-type refrigerant. This second working fluid will flow through an evaporator (heat exchanger). The high pressure steam that is produced moves a turbine that is connected to a generator that produces electricity. After the steam moves the turbine, it is condensate using the cold seawater that is pumped from the depths and is pumped back to the evaporator to start the cycle. The turbines that are use in the closed cycle are usually smaller than the ones use in the open cycle because the density and operating pressure of the second working fluid are higher, see Figure 3.7.

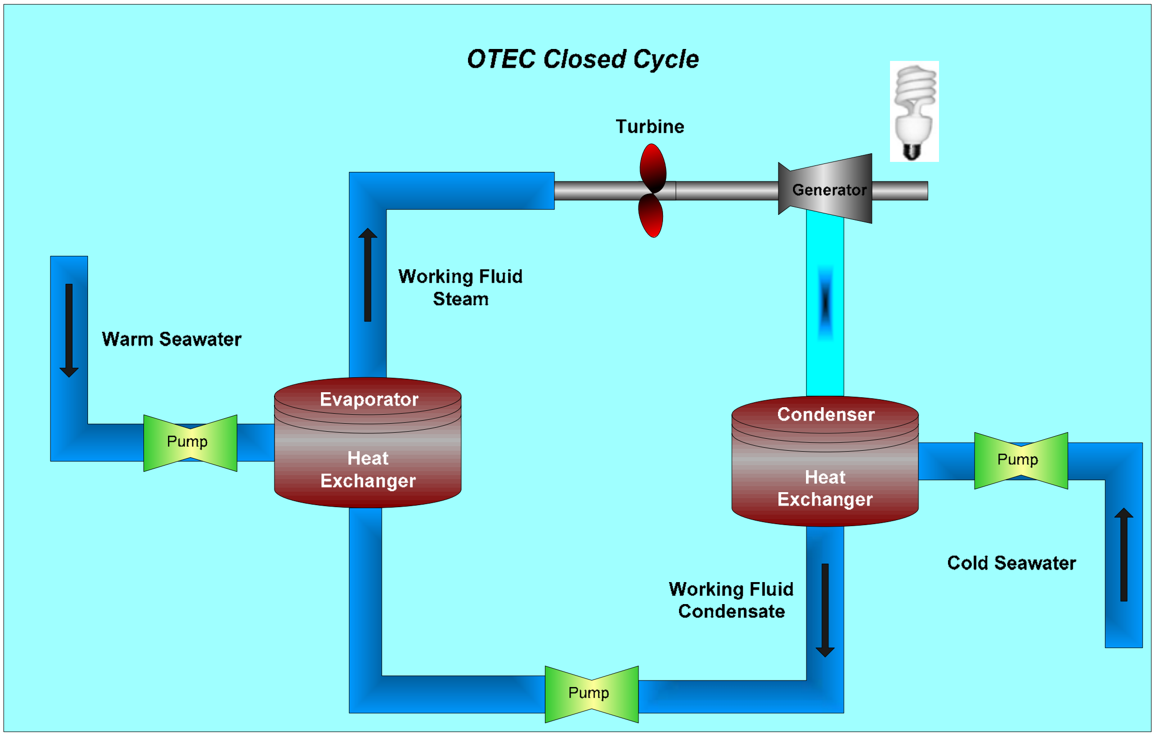

Figure 3.7 Simplified Diagram of the OTEC Closed Cycle Process

3.4.1.2 OTEC classification according to location

OTEC power plants are classifies according to the location where they are built as: land based (shoreline or near shoreline), on a platform (shelf mounted) or floating.

Land based - This type of power plant offers the advantages of: no mooring to the bottom of the sea, avoid the use of electrical submarine conductors and lower the costs of maintenance and operation. In addition these types of plant are protected from storms and heavy seas. However, the cold water pipe has to pass through the beach zone until it reaches the cold water depth (800-1000 m) suffering from friction losses and warming of the cold water. Moreover, this plant facilitates the operation of the mar culture and desalinated water processes.

Platform- These plants can be built on shipyards, towed to the operation location or moored to the bottom of the sea. The main advantage of it is that the cold water pipe is shorter than the one for land based plants. Its costs are higher because it has to be moored, use long transmission electrical conductors and required strong facilities that support the ocean conditions (currents, waves, storms).

Floating- Same as the platforms types the floating ones used shorter cold pipes to pump the cold seawater. Its designing is for off-shore use. The difficulties that it present are: stabilization problems, mooring, power delivery, maintenance and reparation of its components and higher operation and installation costs.

3.4.2 Ocean Thermal Energy Resource in Puerto Rico

Puerto Rico, located near the equator 18°15′ N 66°30′ W, has ocean water temperature gradient from surface to a depth of 1000 meters around 22 to 24 °C as shown in Figure 3.8.

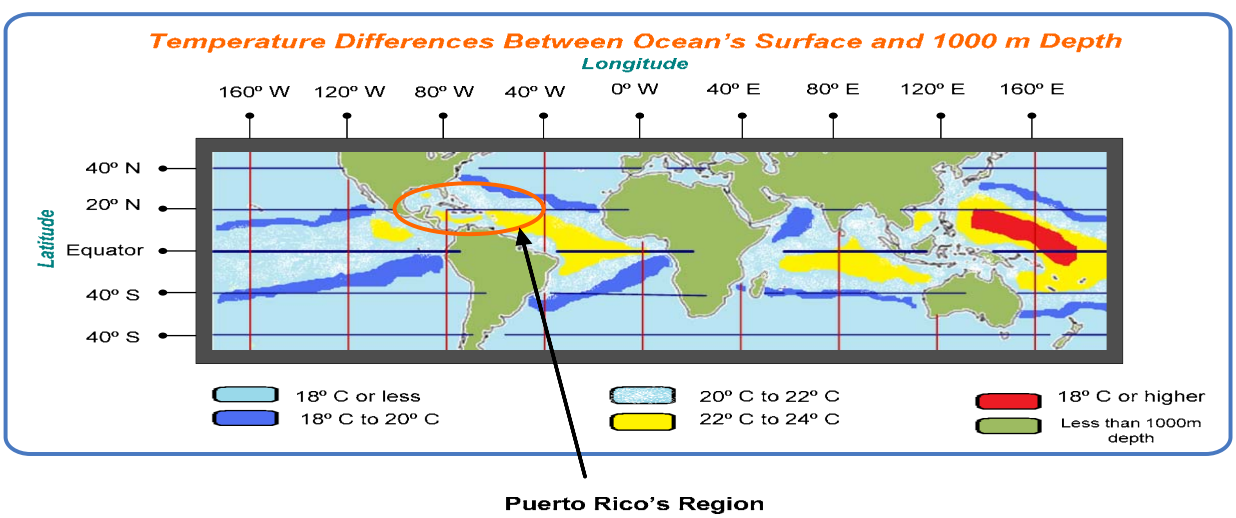

Figure 3.8 Ocean Thermal Gradient for the World

To use OTEC it is necessary to have an abrupt fall into the sea bottom close to shore to obtain the necessary cold water. Staying close to the shore makes the energy transmission, maintenance & operation more economic and efficient. Thus the study of the seafloor, or bathymetry, around the Island is important. A graphical summary of bathymetry results for Puerto Rico is shown in Figure 3.9.

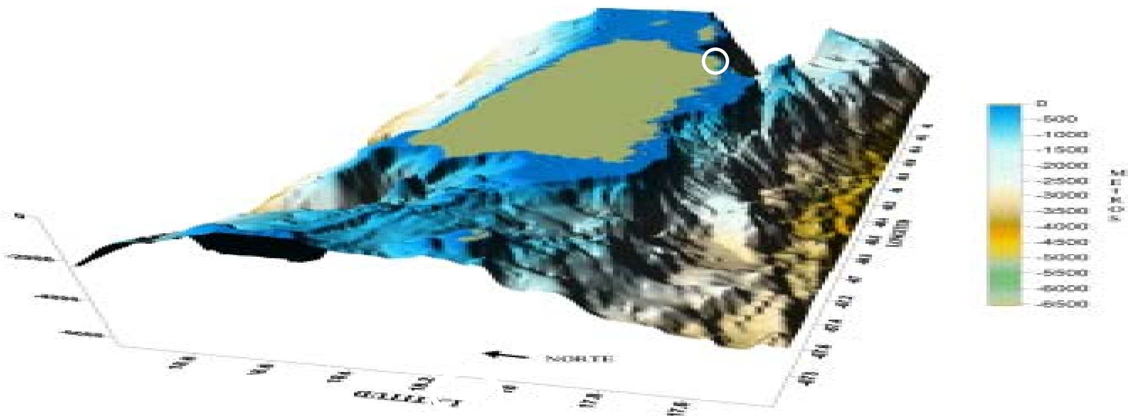

Figure 3.9 Bathymetry of Puerto Rico (Author: Dr. Aurelio Mercado UPRM)

Punta Tuna is located at the south-east coast of Puerto Rico, inside the white circle in Figure 3.9. Directly south of Punta Tuna we find one of the best OTEC sites in the World. The water surface at this place has a temperature between 26° C and 29° C throughout the year. Waters of temperature 6° C can be found at 1000 meters of depth at approximately one mile from the coast. This produces a mean temperature gradient of approximately 22°C. An OTEC plant requires a minimum of 20° C.

In 1980 the United States Department of Energy (DOE) issued a program to develop a closed-cycle OTEC pilot plant. The agencies involve in this projects was the Center for Energy and Environment Research (CEER) and Puerto Rico Electric Power Authority (PREPA). The studies made in Punta Tuna determined a temperature gradient of 22° C at 900 meters of depth.

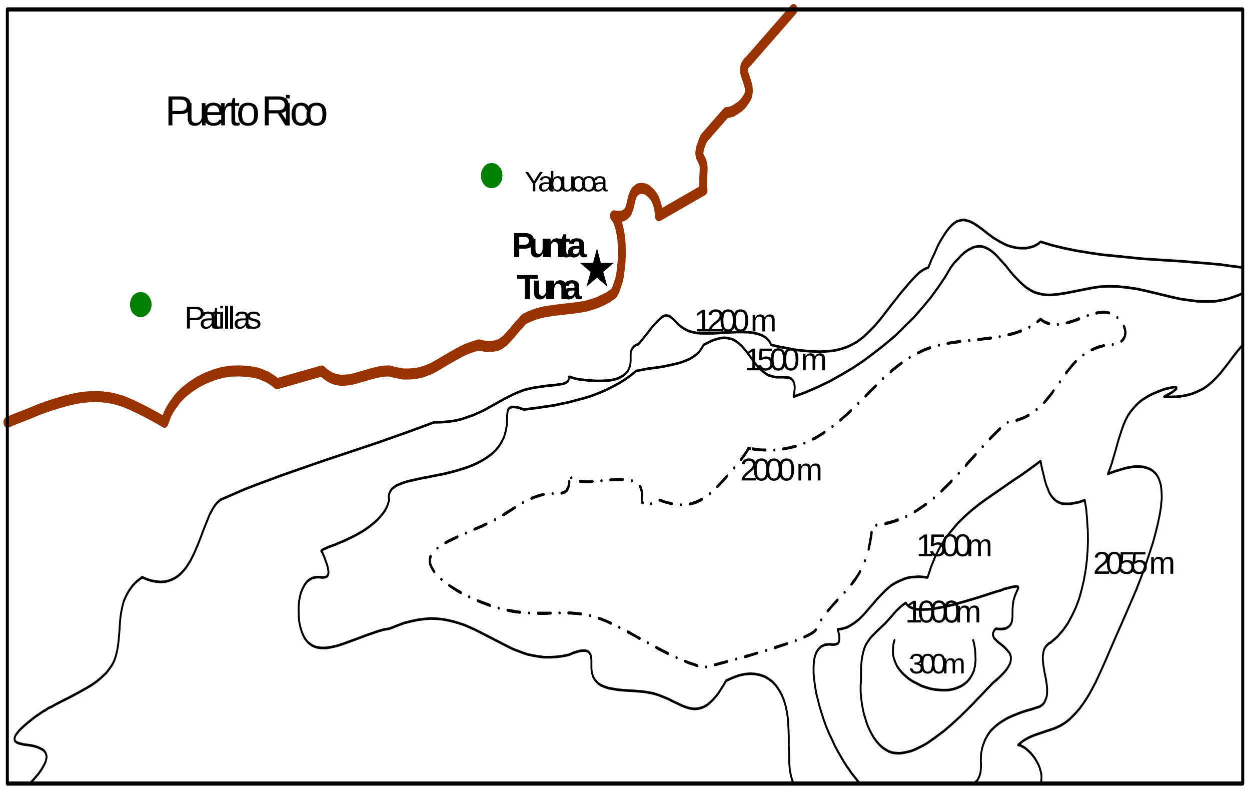

Figure 3.10 Bathymetry near Punta Tuna, Puerto Rico

The immersed vessel "Alvin", 29 feet of length and 24 tons of weight, was used to take samples at 3,600 meters of depth with the purpose of identifying places to sink OTEC towers and install the cold water pipes. Observations closed to Punta Tuna indicated that the seafloor was composed of fracture carbonate rocks not adequate for this type of installation. The "Alvin" was deployed near Caja de Muerto Island, south of Ponce, and a more suitable place was found.

3.4.3 Conclusion on Available OTEC Power for Puerto Rico

No reliable cost data is available to judge the economic feasibility of OTEC technology. Although the concept is well understood and the resource is available in Puerto Rico no one in the World has built a commercial OTEC plant. Funds, private, public or a combination of both, are required to install a prototype facility in the south coast of Puerto Rico. The prototype is needed to identify and possibly overcome the technological challenges; both in construction and operation, that the prototype OTEC plant will certainly produce.

Although private companies exist that claim to have a complete design for an OTEC plant no one of this companies are willing to commit to a purchase power agreement at a fixed kWh sales price.

No evaluation of the environmental impact of OTEC has been produced. The prototype plant will provide real data to evaluate the consequences to the marine environment of operating this technology.

3.5 Ocean Waves Energy

Waves can be formed through the presence of many forces that acts on the ocean surface. The gravitational forces like the one that acts between the Earth, the Moon and the Sun and the geological forces that produce sub sea earthquakes that can generate tsunamis are some of the forces that act on the formation of ocean waves [O25]. But the most common and known form of waves are the ones that are derivative of the solar energy.

When the sun heats the earth surface it generates zones with different pressures that produce winds. As those winds blows over the ocean surface the friction that is created between the wind and the water forms the waves, see Figure 3.11. The increase on the speed of the winds cause that the waves increase on height and mass much faster that in depth.

The size of the waves will depend on three (3) factors [O26]:

- Strength of the winds
- Amount of time that the winds blows
- The distance (fetch) over which it blows

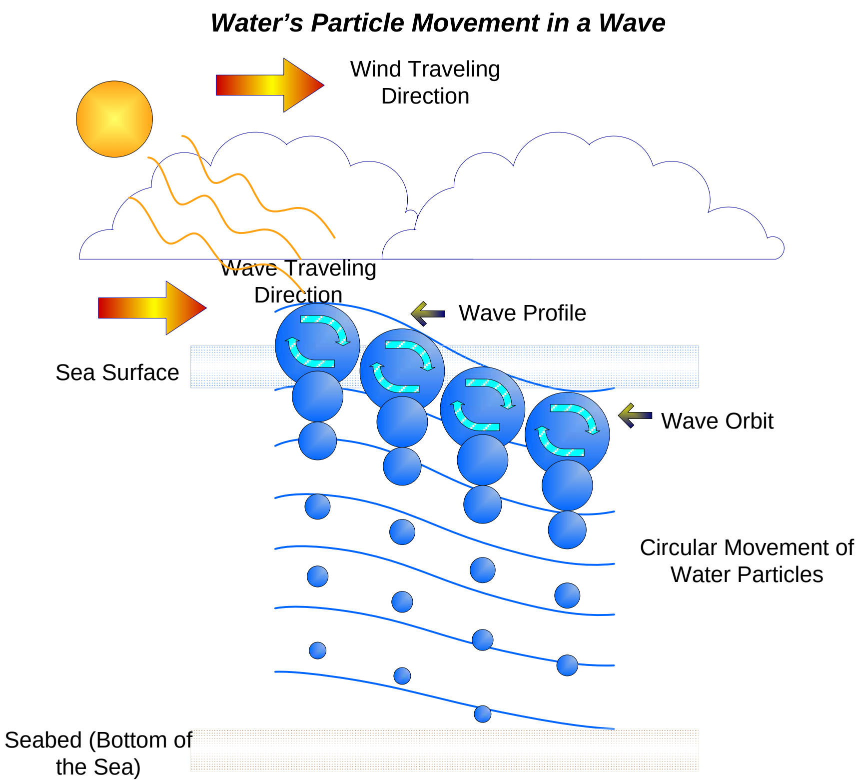

Figure 3.11 Water Particle Movements in a Wave

Waves can be characterized by its height (H), its period (T) and its wave length (λ) [O25]. The wave height is the vertical elevation of the wave crest above the trough; normally it is less than $^1/_7$ of its length [O27]. The wave period is the interval of time that it takes for two wave crests to pass a fixed point and the wave length is the horizontal distance between two crests, see Figure 3.12.

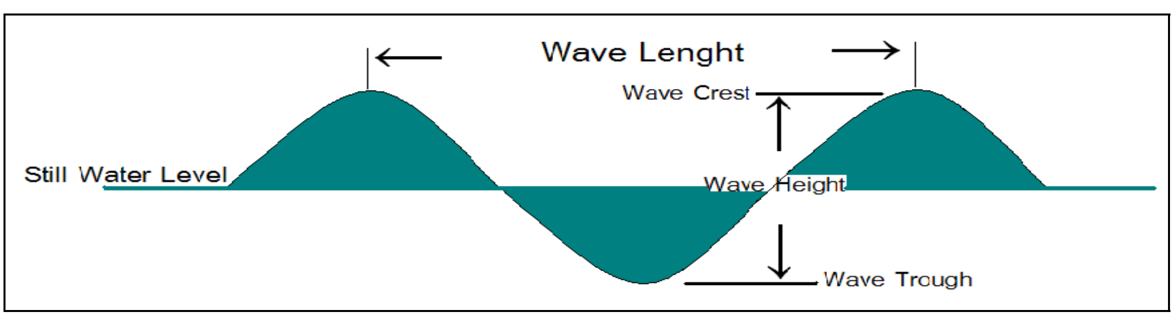

Figure 3.12 Simplified wave characteristics

Ocean waves vary from location because steady wind causes longer wave duration and with the seasons of the year, because the waves are larger on winter than in summer. Ocean waves can be classified in two types: the *local seas* and the *swells. Local seas* are ocean waves generated by the action of the winds on the location that they blow; their length is ten to twenty times their height. The *swells* are a group of long and short waves that can travel thousands of miles from their point of origin, which normally is a storm in the middle of the ocean. These types of waves suffer little attenuation and arrive at distant coasts with fury [O28].

3.5.1 Effects of surroundings in waves

Waves suffer changes as they approach the shore, among these; *refraction, reflection, diffraction, shoaling and* finally *breaking* [O25]. The factor that dominates *wave refraction* is the decrease in the depth of the waters. On shallow waters the velocity (celerity) of the wave train is reduced as long as the water depth decreases. The wave trains tend to adapt its propagation to the contours of the bottom moving parallel to the coast. The period of the ocean waves remains constant but the wave length is reduced and the wave height change. The wave refraction distributes the wave energy along the coast unevenly, creating zones where this energy can converge or diverge. Higher waves are related with zones that converge [O25].

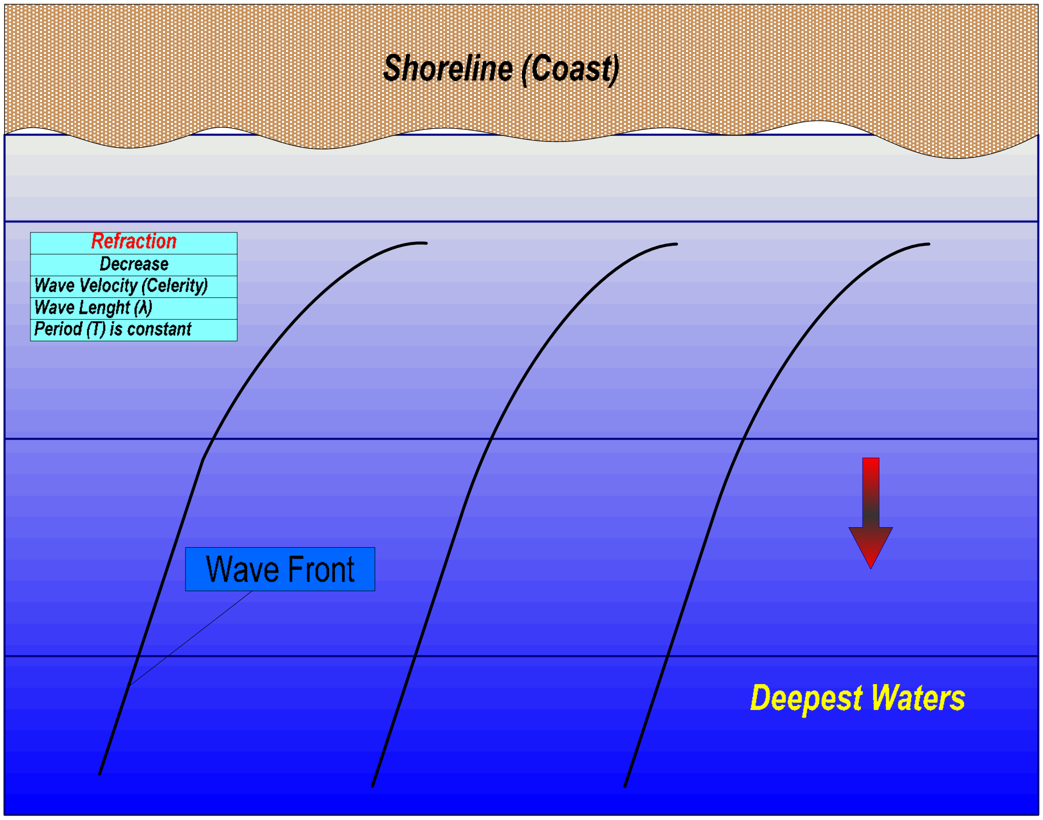

Figure 3.13 Wave Refraction

Wave reflection occurs when the ocean waves strike a vertical object and reflects straight back in such a way that the incidence angle is equal to the reflection angle. A wave of double height is produce because of the addition of the two vertical components. Because the horizontal motions are equal and opposite they could cancel. The effect of reflection causes a minimal loss in the wave energy [O25].

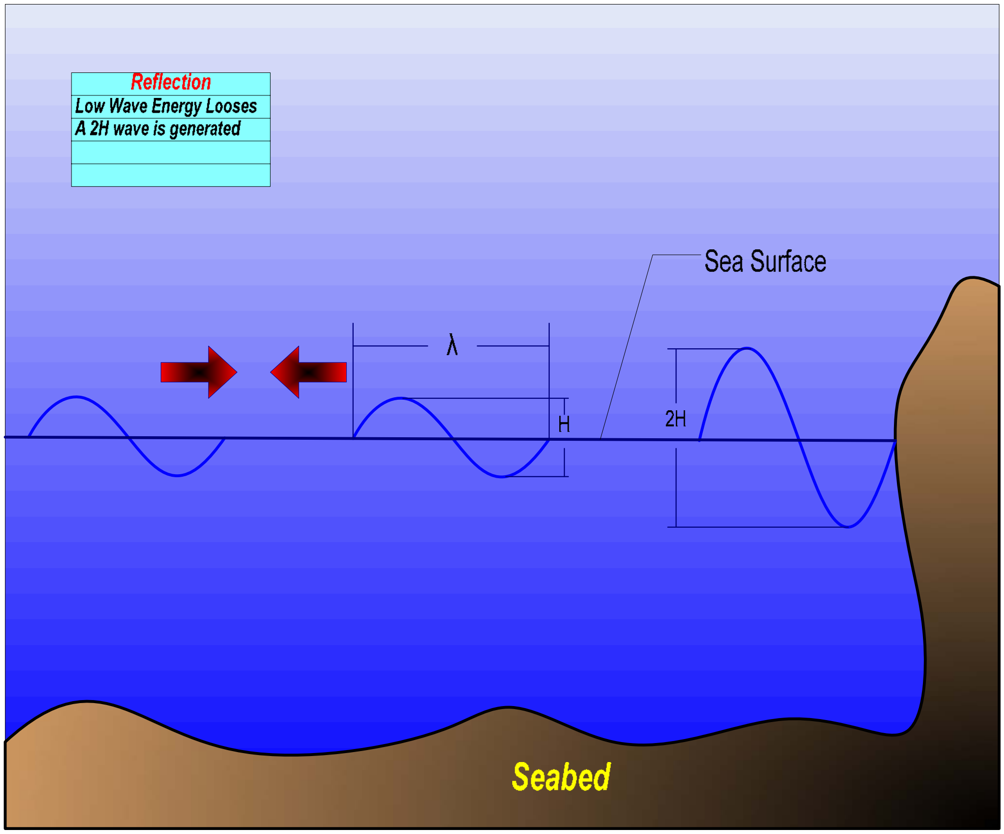

Figure 3.14 Wave Reflection

Diffraction is the result of the bending of waves when they interact with a barrier. These promote the transfer of energy from high energy concentration points to low energy concentration points [O25].

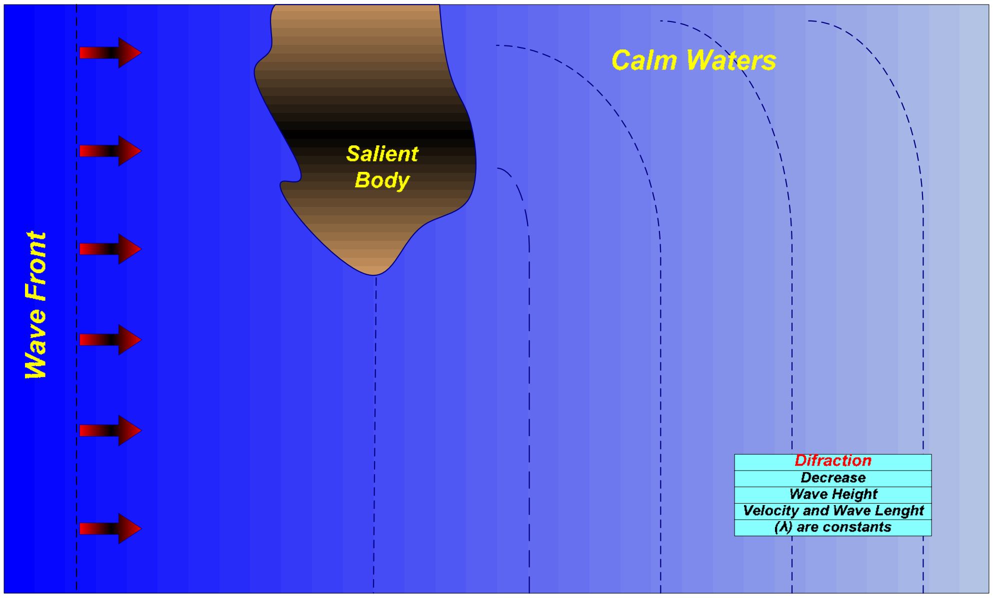

Figure 3.15 Wave Diffraction

Shoaling occur when the wave enter in shallow waters so it losses velocity and length but its height increases [O25].

The *breaking* occurs when the depth of water is approximately the same as the wave height. *Refraction, reflection, diffraction, shoaling and* finally *breaking* are important because they affect the wave's energy thus affecting the amount of electrical energy that can be obtained from the waves [O25].

3.5.2 Measured and Calculated Wave Energy

The generation and propagation of ocean waves are nonlinear processes. The real sea is a superposition of irregular wave trains which differ in period, height and direction. The local behavior of the sea state can be represented by a spectrum, $S(f,\theta)$. The *spectrum specifies how the wave energy, proportional to the variance of the surface elevation, is distributed in terms of frequency and direction [O44]*. The parameters of wave height, period and direction summarize the spectrum.

For wave height we can use significant wave height, H_s , which is defined as the average of the largest one third (1/3) of the waves in a wave train record. This matches the visual impression of wave heights [O44, O45]. It can be computed from the spectrum using the expression:

$$H_s = 4m_0^{1/2}$$ **Equation 3-1**

Where m_0 is the zero-th spectral momentum from [O45], and

$$m_n = \int_0^{2\pi}\int_0^{\infty} f^n S(f,\theta)dfd\theta$$ **Equation 3-2**

m_n is the n-th momentum of the directional energy distribution.

For wave period two definitions are used in the literature: the peak period, T_p, and the mean or energy period, T_e [O44]. The mean period depends of the lower frequency band which contains most of the energy and is defined as

$$T_e = \frac{m_{-1}}{m_0}$$ **Equation 3-3**

The peak period is the inverse of the peak frequency.

$$T_p = \frac{1}{f_p}$$ **Equation 3-4**

Using these parameters we compute the wave power, or energy flux per unit crest length, as

$$P = \rho g \int_0^{2\pi}\int_0^{\infty} c_g(f,h) S(f,\theta) df d\theta$$ **Equation 3-5**

where,

Water density: $\rho = 1.025\ g/m^3$

Acceleration due to gravity: $g = 9.81\ m/s^2$

Group velocity in deep water: $c_g = \frac{g}{4\pi f}$ **Equation 3-6**

The wave power is now computed using

$$P = \frac{\rho g^2}{4\pi} m_{-1}$$ **Equation 3-7**

Using equations 3-1 and 3-3 we can express wave power in terms of H_s and T_e to obtain

$$P = \frac{\rho g^2}{64\pi} H_s^{\ 2} T_e$$ [O44, O45] **Equation 3-8**

Expressing H_s in meters and T_e in seconds we obtain the approximate expression

$$P \cong 0.5 H_s^{\ 2} T_e (kW/m)$$ **Equation 3-9**

Although Equation 3-9 uses the approximate 0.5 factor, in reality this varies from 0.3 to 0.5 depending on the relative amount of energy in local sea and swells and with the spectrum used. The 0.5 multiplier applies to any sea state represented by a two-parameter Bretschneider spectrum [O44, O45].

Wave power not only changes with the world localization, it changes with the season of the year. Studies made in the states of Oregon, Hawaii and Maine indicates that the wave power density is high during the months of November thru February and reaches its lowest point during the summer near the months of July and August [O30, O31, O32, O33].

A reliable data base on the local ocean wave's behavior is not common. Although a variety of methods and systems exists to develop the required information in many places studies and information on wave energy are few and in some cases don't exist. Wave data sources usually take measures of wave height, wave period and wave direction.

In the past the most common way to record ocean wave data was using ship observations. The Summary of Synoptic Meteorological Observations (SSMO) is one of this well known data sources [O34]. The main disadvantage of the observation method is that it introduces a lot of human error and that for safety reasons ships do not take measurements on areas of difficult weather conditions.

The installation of buoys is another way to take wave measures. The NOAA National Data Buoy Center (NDBC) has measuring buoys on different parts of the world.

Another method is the use of computer models. The wave hind cast models consist of software that generate based on input atmospheric pressure the ocean surface winds. With those winds the model derives the associated waves. The US Army Corps of Engineers developed a model known as the Wave Information Study (WIS) [O34, O35]. The study recorded data for a period of 20 years.

3.5.3 Wave Energy Resource around the World

Great Britain, Portugal, Japan, Spain and the United States of America, specifically the states of Oregon, Hawaii, Washington and Maine, are studying the possibility of using ocean wave energy to produce electricity. The focus of these studies is to improve the efficiency of energy conversion devices, to develop new technologies and identifying the best places to capture wave energy and convert it to electrical energy.

The Electrical Power Research Institute (EPRI) made a study including the states of Oregon, Hawaii [O30, O31, O32, and O33]. These studies included an overview of the energy situation on the United States followed by a site characterization, bathymetry and grid interconnection overview. Also they list the uses of ocean space, the regulatory agencies and permitting requirements.

3.5.4 Wave Energy to Electricity Conversion

There have been several wave energy conversion devices developments over the past years. The developments can be divided in four principal groups: the oscillating water column, the attenuators, the overtopping and the point absorbers [O36, O37]. These devices are on the state of development and test and companies have plans on building small power plants in different countries especially on Europe [O38].

In the United States the state with most developments in this area is Oregon. The University of Oregon has developed a Permanent Magnet Linear Generator Buoy Device and has tested the device in tanks that simulated waves. Recently the Aqua Energy Company has deployed the AquaBuOY 2.0, a point absorber, in the coast of Oregon at only 2 miles from the shore. Its purpose is to compile and record information regarding the ocean characteristics and device parameters to construct a wave power plant [O39].

The Ocean Power Delivery company was established in 1998 to develop the Pelamis Wave Energy Converter, an attenuator. In August 2004 a 750kW full-scale Pelamis was connected to the United Kingdom grid. This device was tested at the European Energy Centre.

The Japanese have been the main developers of the oscillating water columns (OWC). The OWC consists of an air column that is moved up and down by the motion of the waves. This air moves a turbine and the turbine a generator. In general, this device used a bidirectional turbine also know as Wells Turbine. The company Energetech is developing a new bidirectional turbine for their own OWC.

3.5.4.1 Description of Devices

There are four main types of wave energy conversion devices. These are the attenuators, point absorbers, terminators or oscillating water column and the overtopping devices [O40]. These devices can be use to extract wave energy at the shoreline, near-shore or offshore.

The *attenuators* are multi-segment floating devices oriented parallel to the wave direction [O40]. The waves caused the segments to flex. These segments are connected to hydraulic pumps or converters. The most mature example of the attenuator technology at this moment is the Ocean Power Delivery *Pelamis*. This is a hydraulic floating cylinder of 150 meters of length that has a power rating of 750 kW. It consists of 4 connected sections that move relative to each other. Also there is the McCabe wave pump that have three pontoons linearly hinged together and also is located parallel to the wave direction.

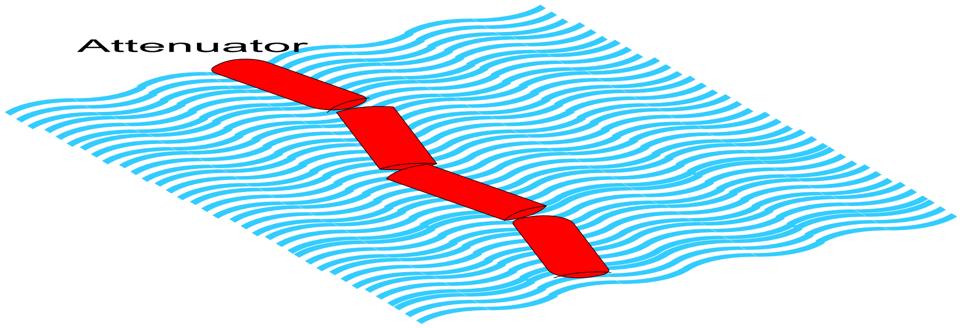

Figure 3.16 Attenuator

The *point absorber* uses the rise and fall of the wave to generate electricity [O40]. The technologies of AquaEnergy with the *AquaBuOY* and Ocean Power Technology with the *PowerBuoy* are examples of point absorbers. There is also the *Archimedes Wave Swing* which consists of a floater that moves the actuator of a permanent magnet linear generator to produce electricity from the potential energy of the waves.

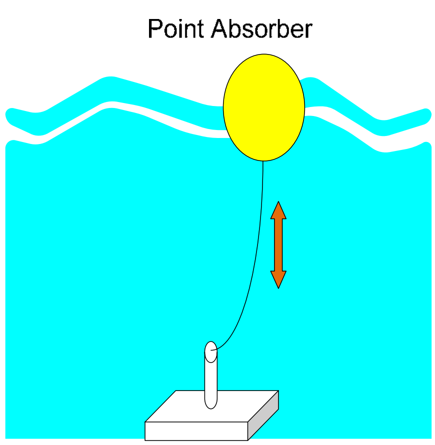

Figure 3.17 Point Absorber

The *terminator or oscillating water column* is a device which consists of an air chamber located above the ocean's surface. When the wave enters the chamber it makes the water level to rise and fall increasing and decreasing the air pressure in the cavity. The air drives a turbine and the turbine a generator. Because the direction of the air flow changes a Wells Turbine, that is a bidirectional air turbine, is used. One example of the oscillating water column is the Energetech *Oscillating Water Column* [O40].

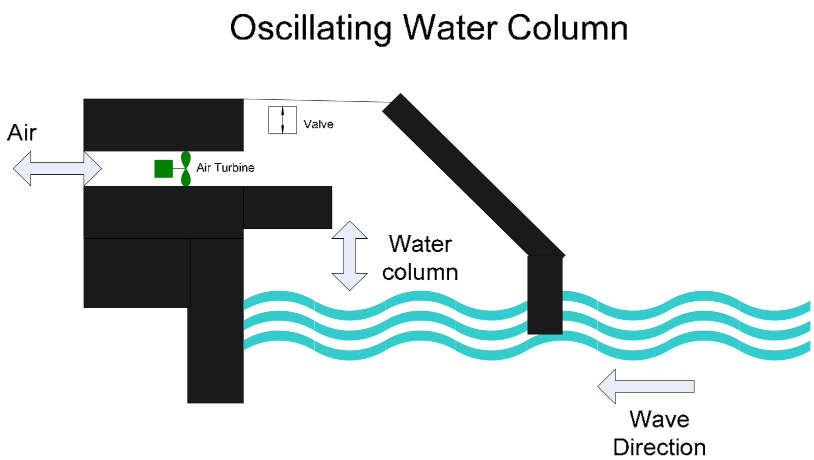

Figure 3.18 Oscillating Water Column

The overtopping device is one in which the waves roll into a collector and funnels the water into a hydro turbine coupled to a generator. One example of these devices is the *Wave Dragon* [O40, O41]. Table 2.1.4 summarizes the wave energy converter devices.

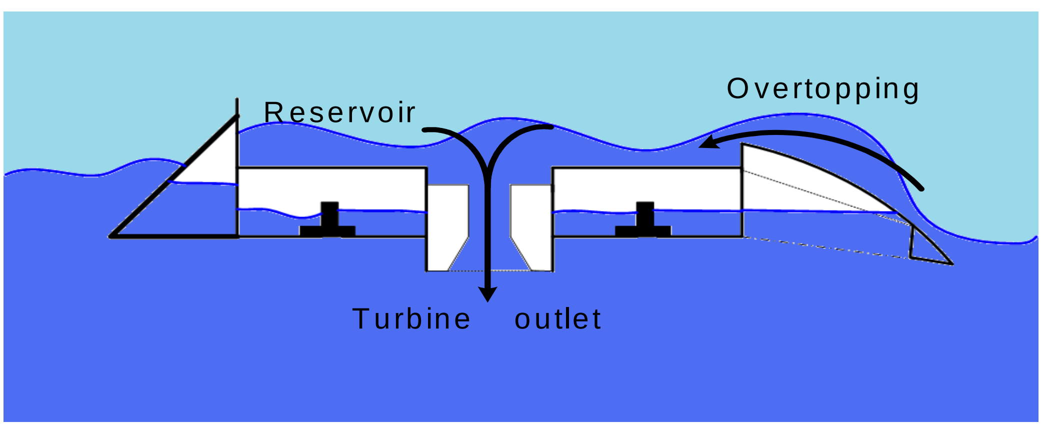

Figure 3.19 Overtopping

Table 3.6 Summary of Wave Energy Devices

Device	Technology	What component of the wave movement uses?	Installation	Examples
Terminator	Consist of an air chamber whose air is forced to move by the rise and fall of the wave entering the chamber and it is extended perpendicular to the wave direction.	Vertical movement	Onshore, near-shore, floating offshore	Energetech OWC, JAMSTC Mighty Whale
Attenuator	Floating structures that consist of multiple segments hinge together by hydraulic pumps and it is extended parallel to the wave direction.	Vertical and horizontal movement	Offshore	OPD Pelamis, McCabe Wave Pump
Point Absorber	Uses the rise and fall of the wave in a single location.	Vertical movement	Offshore, near-shore	OPT Power Buoy, Aqua Energy Group Aqua Buoy, Archimedes Wave Swing
Overtopping	This device has reservoirs fill by the waves with water. Then the water is released through a funnel to drive hydro turbines.	Vertical and horizontal movement	Onshore, floating offshore	Wave Dragon, Wave Plane

3.5.5 Other Considerations

Proper evaluation of any proposed technology requires the study of social, environmental, and legal issues. The following is a brief list of topics to be considered when addressing some of these issues.

Environmental

Although electricity production from wave energy does not produce atmospheric pollutants, like carbon dioxide, nitrogen oxide and sulfur dioxide, during their operation, there are emissions of these gases during the manufacturing of components, the process of materials and the development of infrastructure [O27]. These emissions are less than those by coal generation so wave energy can help reduce the emission of these gases.

There are other environmental considerations that need study. There is the visual impact of near-shore installations. Other potential consideration is the noise of some turbines, but this can be reduced considerably. The reduction in wave height has to be considered especially near surfing beaches. The impact on the waves can be observed 1 to 2 km away from the device in the direction of the wave travel [O36]. There have to be careful selection of the sites used to install these devices to avoid interference with fishing, shipping, recreational boating or other uses of the seas.

Legal

The exploitations of wave energy in international waters must be addressed since a country that choose to exploit wave energy in international waters, before swells reach the coast of other countries, will affect the wave energy resource of the last ones. International regulations are needed to resolve this possible conflict [O27].

Economics

Electricity production from wave energy is not a mature technology so costs associated with can be high. Since projects are new developers have no financial or economic model to take as reference, as it was with wind energy projects years ago [O42, O43]. Years ago wind energy projects needed incentives to become commercially viable. Us Federal Law, such as EPAct 2005, provides some incentives for wave energy use. Examples are [O42]:

- *Market push policies* to reduce the cost of renewable energy for the customers,
- *Market pull policies* to reduce renewable development cost or increase revenues,
- *Indirect cash assistance*, a tax incentive to the operator,
- *Direct cash assistance* a cash subsidy to the wave energy developer,
- *Low-cost debt financing* a decreased cost incurred by project financiers to acquire capital by loan strategies, and
- *Customer choice*, the right of the customer to purchase electricity generated by renewable sources.

3.5.6 Wave Climate and Coastal Regions in Puerto Rico

Puerto Rico has four major coastal regions: north, south, west and east. Each region is characterized by different local climate and geological conditions. In terms of wave climate the wave patterns for the Island are complex because it is affected by three wave regimes [O34].

- *Easterlies Seas* - This wave regime affects the entire island coastline except for the west coast. It approaches from the northeast to the southeast producing low energy seas [O34].

- *North Atlantic Wave Regime* - This wave regime travels long distances from the middle latitudes where it is generated to the coasts of Puerto Rico. The north coast and the west coast are the ones that are affected by this regime [O34].

- *Caribbean Wave Regime* - This wave regime affected primarily the south coast. This regime is characterized for wave heights smaller than those from the North Atlantic Regime but higher than the Easterlies Seas [O34].

North Coast - This coastal region is composed, from west to east, by the municipalities of Isabela, Quebradillas, Camuy, Hatillo, Arecibo, Barceloneta, Manatí, Vega Baja, Vega Alta, Dorado, Toa Baja, Cataño, Guaynabo, San Juan, Carolina, Loíza, Río Grande and Luquillo. The influence of Atlantic swells that travel long distances without barriers, storms and cold fronts are some of the aspects that make this region the one with the higher wave energy levels. In addition this coast faces the Puerto Rico Trench a deep section in the ocean floor that dramatically reduces bottom friction on the waves. During the months of November to April large swell (3-3.5 m) and long periods (12-16 s) are common because of the arrival of cold fronts. The normal wave heights ranges are from 1.2-1.8 m, similar to those of the west coast [O34].

West Coast - This coastal region is composed, from north to south, by the municipalities of Aguadilla, Aguada, Rincón, Añasco, Mayaguez and Cabo Rojo. The west coast is coastal region most protected from winds. Puerto Rico shields the west coast from the tropical storm systems that approach from east, northeast and southeast, the most common. This region is affected by deep water wave heights from 1.2 to 1.8 m. On the northwest side, especially at Rincón high amplitude waves and swells are normal [O34].

South Coast - This coastal region is composed, from west to east, by the municipalities of Lajas, Guanica, Yauco, Guayanilla, Peñuelas, Ponce, Juana Díaz, Santa Isabel, Salinas, Guayama, Patillas, Arroyo and Maunabo. This area is affected by sea swells coming from the south, southeast and the east. The levels of wave energy tend to decrease from south to east. Natural barriers, mangroves and sand bars are present all along the coast. Only when the easterlies are present high amplitudes and long periods waves occur especially during the summer and winter. Swells are common with the presence of storms [O34].

East Coast - This coastal region is composed, from north to south, by the municipalities of Fajardo, Ceiba, Naguabo, Humacao and Yabucoa. This area is surrounded by many natural barriers, such as coral reefs and a cay system between Fajardo, Culebra Island and Vieques Island that acts like a natural breakwater. Short periods and (3-5 s) and low amplitude (0.3-0.92 m) waves are common on this region. During the summer and winter season and increase on the wave energy levels occurs because of the presence of the easterlies [O34].

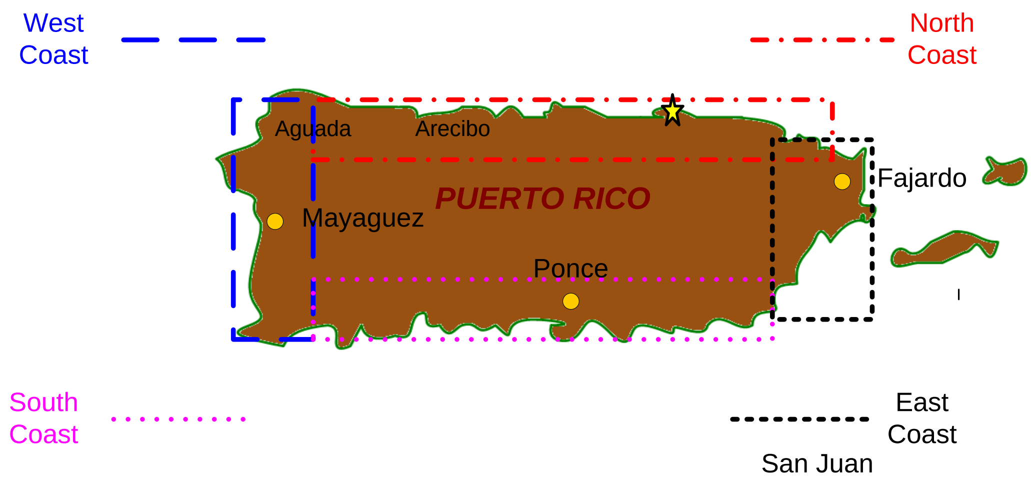

Figure 3.20 Puerto Rico Coastal Regions

3.5.7 Wave Energy in Puerto Rico

There is no instrument-based wave data for the island of Puerto Rico. The majority of published work that has been done on ocean waves in Puerto Rico is related to coastal environmental impact. Wave data sources known for Puerto Rico are the Summary of Synoptic Meteorological Observations (SSMO), from 1963 through 1972, and the Wave Information Study (WIS), from 1956 through 1975 and from 1980 to 1999 [O27, O35].

The SSMO data covers four areas of Puerto Rico, the north, south, Mona Passage and Vieques. Half the data from the Mona Passage is for the north coast so it does not represent the conditions of the west coast. Three quarters of the Vieques area data are from north of La Cordillera, a chain of islands at the east of Puerto Rico, thus it does not represent the conditions of the east coast.

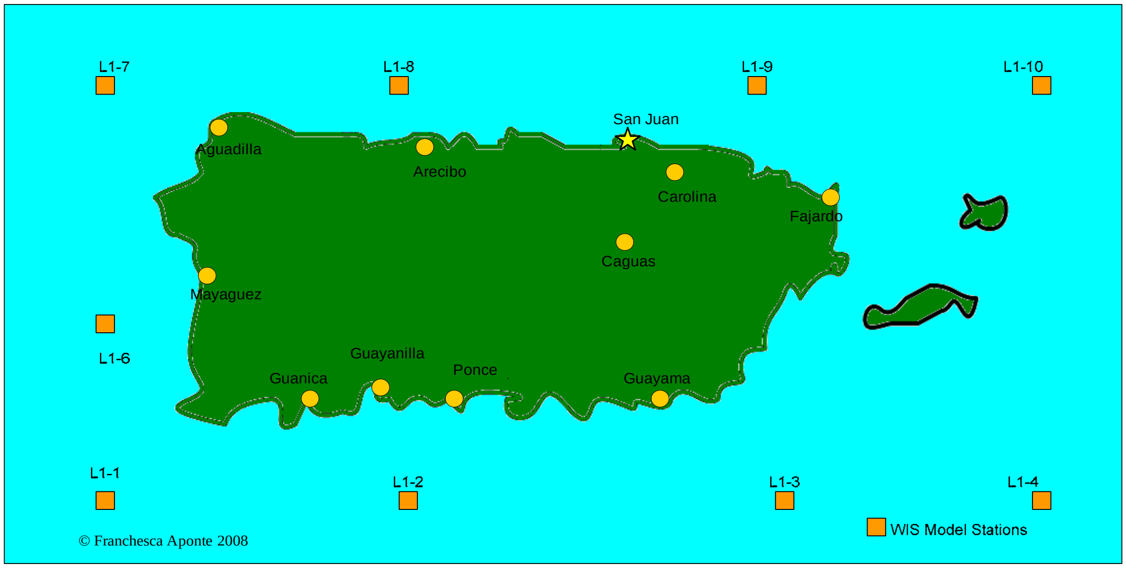

Figure 3.21 WIS Stations around Puerto Rico

The Summary of Synoptic Meteorological Observations (SSMO) was taken by observations from ships, introducing human errors. Also the ships do not enter areas of bad climate and the observations lack wave direction information.

Another data set comes from the WIS model produced using wind data derived from twenty years of atmospheric pressure observations every six hours [O35]. The forecast of the waves with this model do not included the effects of tropical storms or the effect of wave-current interaction.

Another study *The Wave Transformation Study for Selected Puerto Rico Sites in Support of a coastal Erosion Study* [O27] presents wave information for the north coast of the island based on Synoptic Meteorological Observations (SSMO) and Wave Information Study (WIS). The data was compiled for twenty years which include the years of 1956 to 1975 [O27, O35]. This study was based on the north coast of the island because is the one that receive more energy from the local seas and the swells that arrive from the storms passing through the North Atlantic Ocean. Recently, data additional was published by WIS for the years of 1980 to 1999.

A compilation of these data sets and subsequent processing yields the ocean wave data resource map for Puerto Rico shown in Figure 3.22.

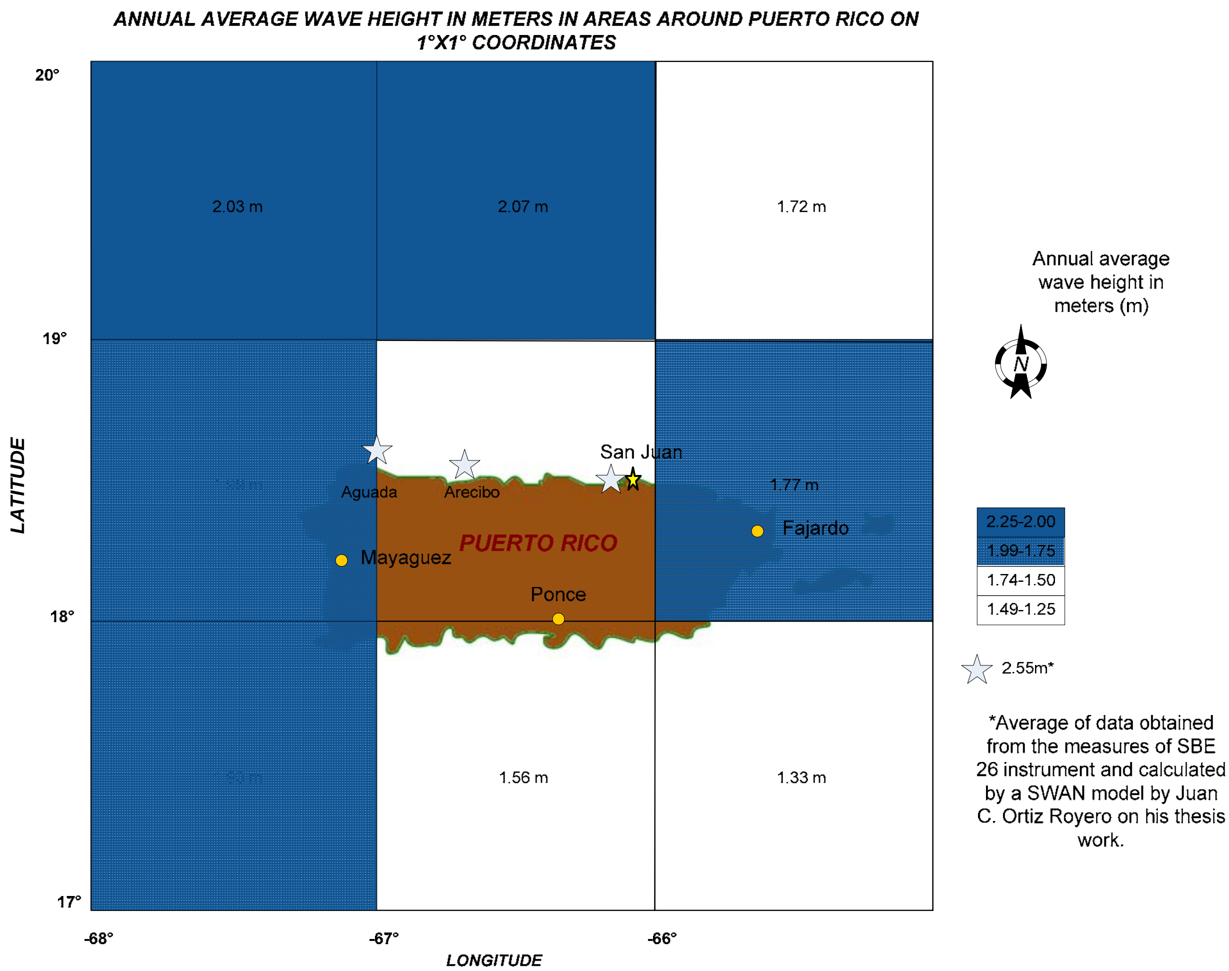

Figure 3.22 Puerto Rico Average Wave Heights [Produced using data from O27].

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