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.

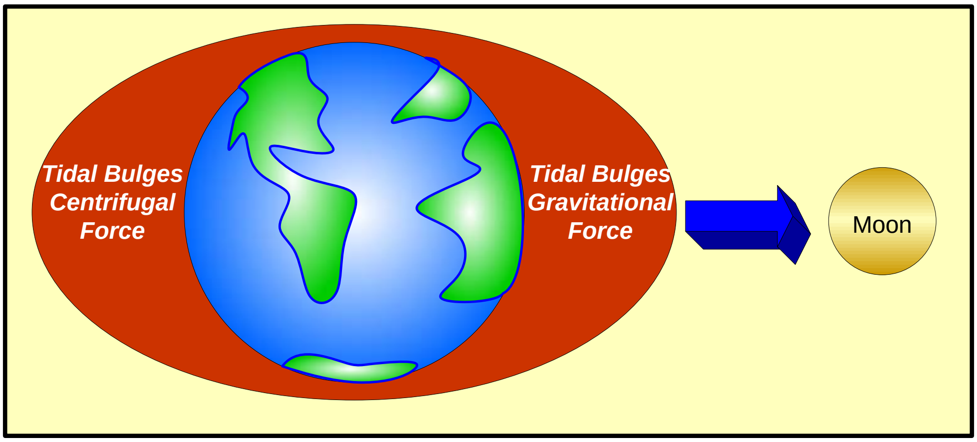

Figure 3.1 Tidal Bulges due to the Gravity and Centrifugal Forces

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.

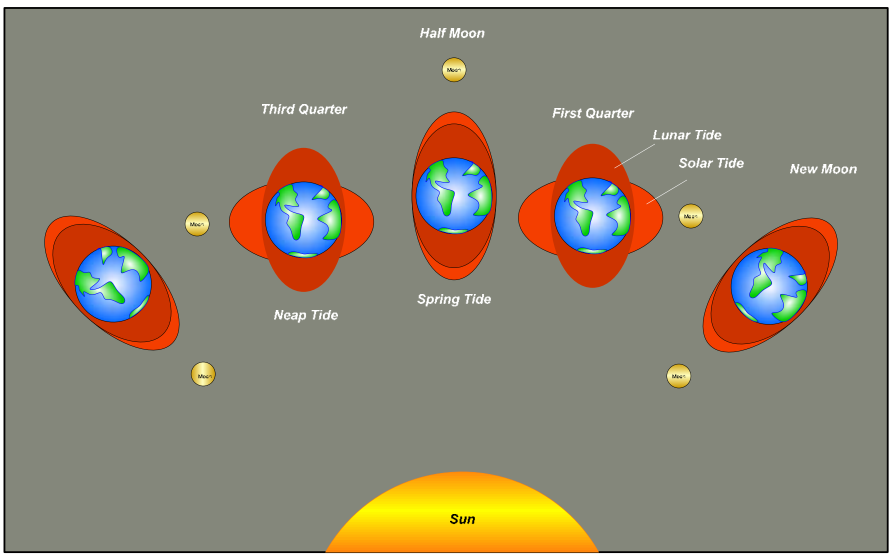

Figure 3.2 Neap and Spring Tides

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].

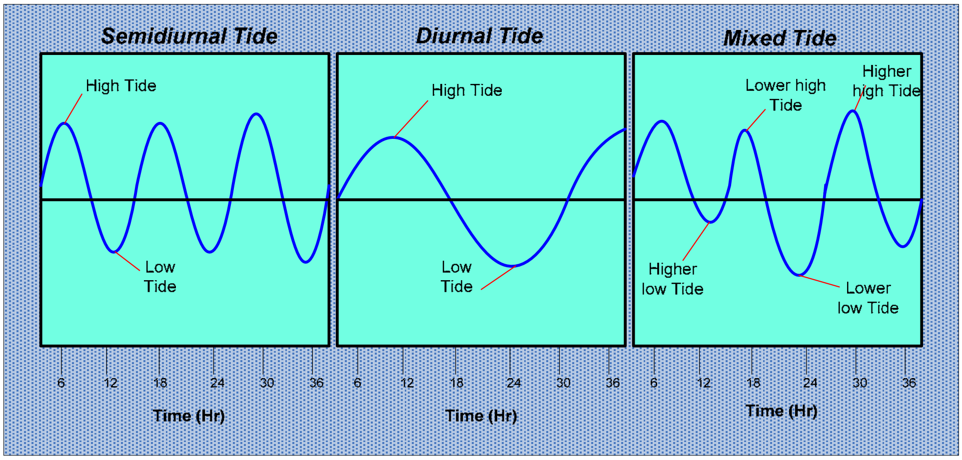

Figure 3.3 Types of Tides

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.