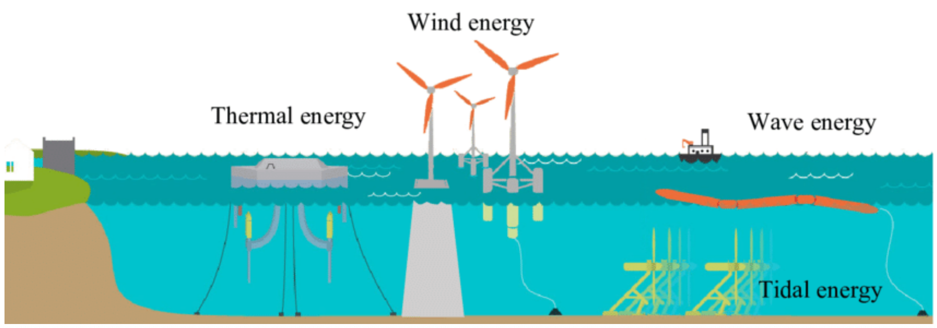
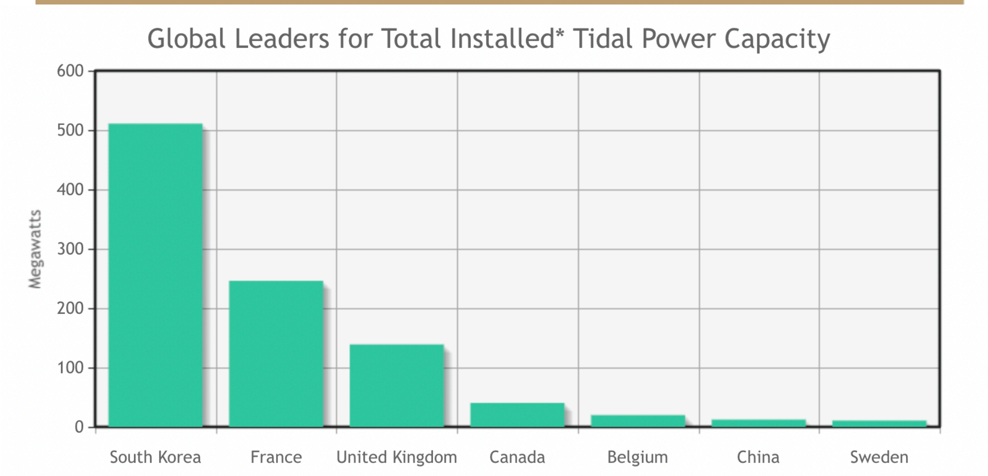
CHAPTER 4
Ocean Energy





Oceans are an enormous reservoir of energy. This energy is stored in form of mechanical energy in waves and tides and thermal energy due to the difference in temperature.
In this chapter those 3 main forms will be explored.

4.1. Ocean thermal energy

Due to solar radiation, the ocean surface is significantly hotter than at deeper locations. In certain regions of the globe, the surface temperature can reach up to 28°C while at about 1 km below the surface, the temperature is around 4°C.
In this case, we can consider using a heat engine running between the hot reservoir at 28°C and the cold reservoir at 4°C. The principle of power production based on this temperature difference in the ocean is called **Ocean Thermal Energy Conversion (OTEC)**.

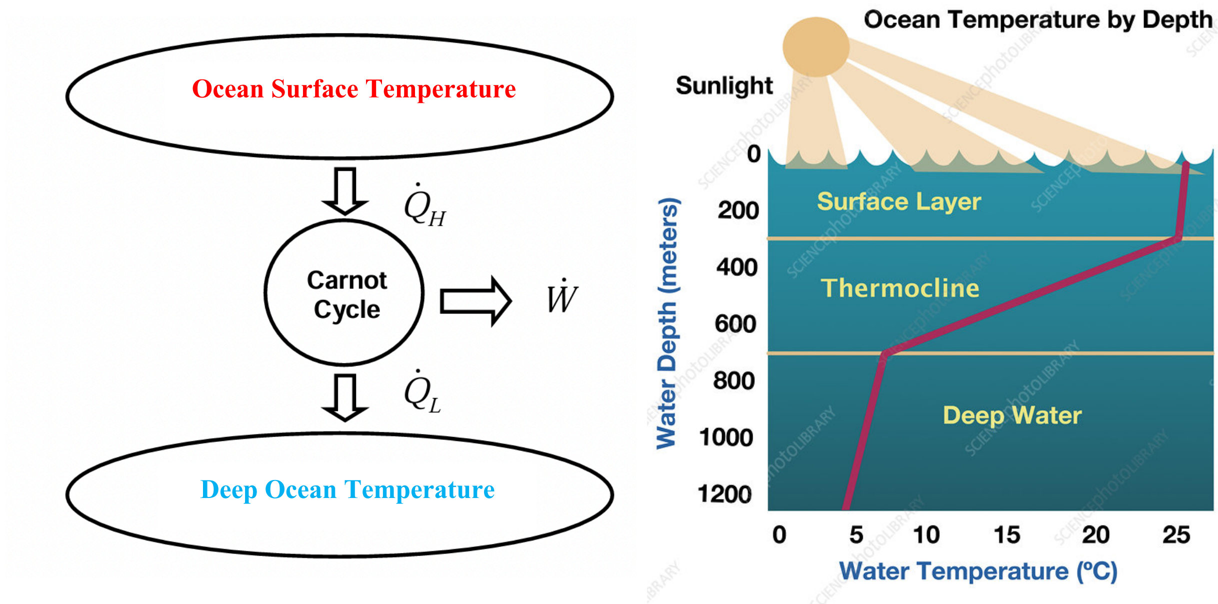


Figure 4.1. Basic principle behind Ocean Thermal Energy Conversion (OTEC).

One main disadvantage of OTEC is the small temperature difference. Indeed, if we compute the maximal efficiency of a heat engine running between 28°C and 4°C, we get:

$$\eta|_{\text{Carnot}} = 1 - \frac{T_L}{T_H} = 1 - \frac{4+273}{28+273} = 0.08 \text{ or } 8\%$$

This represents the maximum possible, while in real life, due to irreversibilities, the thermal efficiency is barely around 3%.
An example of OTEC is the one implemented and operated in Hawaii since the 90s that produced 100 kW (onshore OTEC) and anticipated 100 MW using offshore mode. Note, however, that about half of the power produced was used internally for pumps and other auxiliaries.

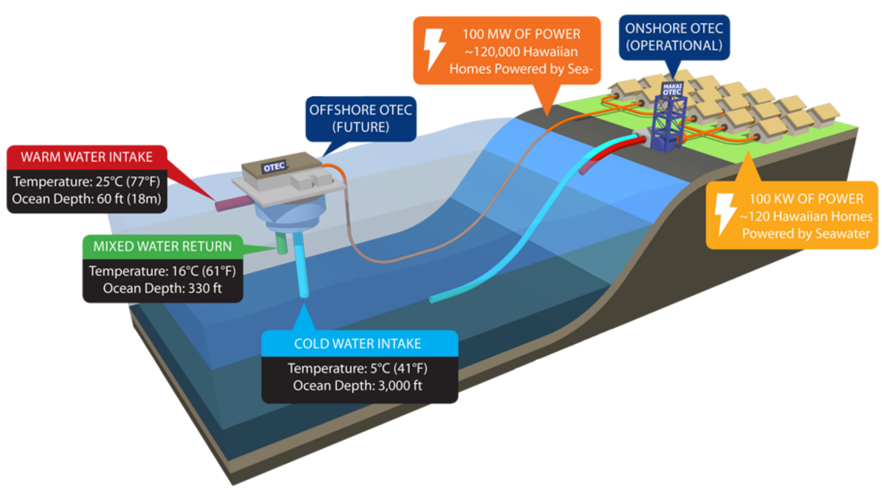


Figure 4.2. Ocean Thermal Energy Conversion (OTEC) in Hawaii with onshore and offshore configurations.

Therefore, to generate a significant amount of power production, the installation needs to be very large. For example, consider an OTEC to produce 100 kW of work at a thermal efficiency of 3%. What is the surface area of the evaporator (consider a log mean temperature of 5°C and heat transfer coefficient of 1.5 kW/m^2 °C):

$$\dot{Q}_{in} = \frac{\dot{W}_{net}}{\eta} = \frac{100}{0.03} = 3333 \text{ kW}$$

and

$$\dot{Q}_{in} = h \times A \times \Delta T$$

Then

$$A = \frac{\dot{Q}_{in}}{h \times \Delta T} = \frac{3333}{1.5 \times 5} = 440 \text{ m}^2$$

(This roughly represents the area of a standard basketball court)

Two main designs exist for OTEC, open and closed systems.

Closed OTEC system	**Claude cycle**
Open OTEC system	**Anderson cycle**

4.1.1. Open OTEC systems

The figure below shows a diagram for an open OTEC system along with its T-h diagram:

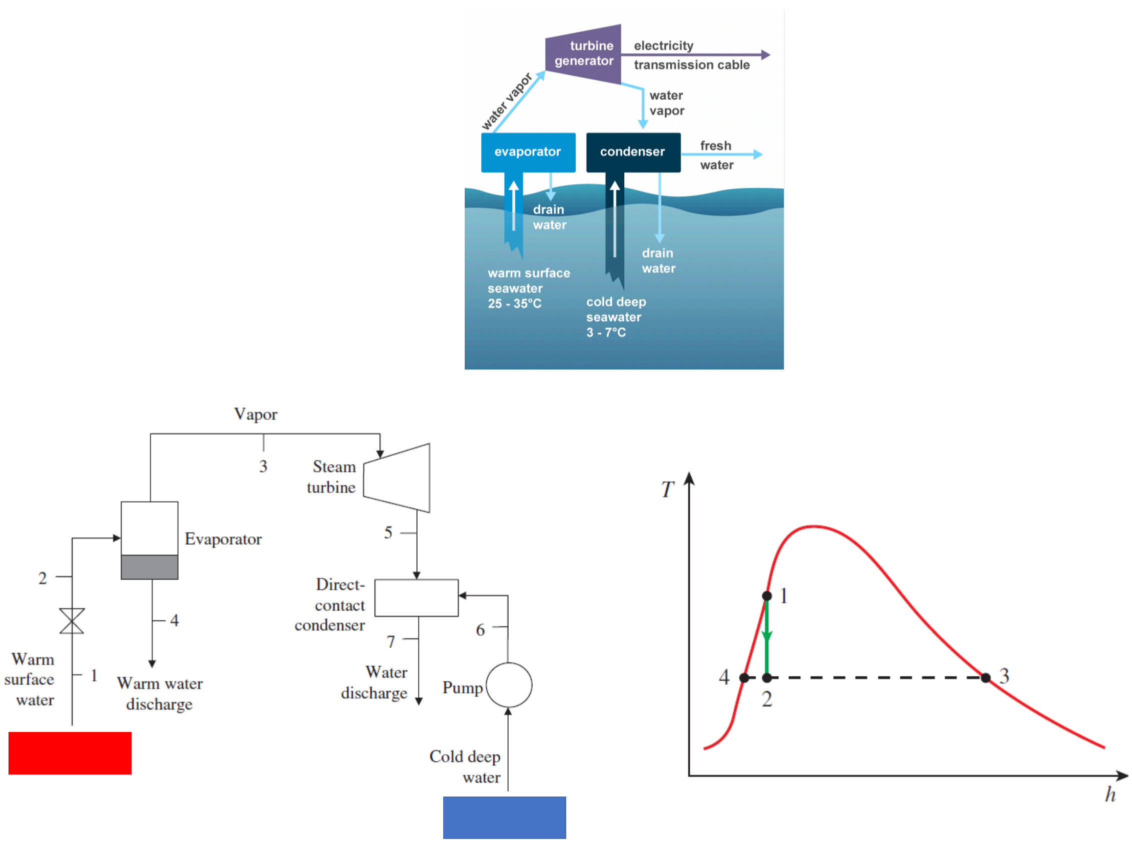


Figure 4.3. Open Ocean Thermal Energy Conversion (OTEC) system and the corresponding T-h diagram.

Note that the specific volume at the entrance of the steam turbine is very high compared to classical steam power cycles. The design of the turbine therefore needs to be different and is very large to handle the high volumetric flow rates.

Example 4.1

The Makai Ocean Engineering OTEC plant in Hawaii, a real-world example of an open-cycle OTEC system, uses warm surface seawater to generate power. Assume an open-system OTEC plant operating under the following conditions:

- Surface seawater temperature: 30°C
- Deep seawater temperature: 10°C
- Evaporator pressure: 3 kPa
- Condenser pressure: 1.5 kPa
- Mass flow rate of warm surface water entering the evaporator: 100 kg/s
- Turbine isentropic efficiency: 85%

This OTEC system uses the warm surface seawater to evaporate low-pressure water into steam, which expands through a turbine to produce power. The steam is then condensed using cold deep seawater from a depth of approximately 1000 meters. Neglecting the pumping power and auxiliary power consumption, determine:

(a) The mass and volume flow rates of steam at the turbine inlet.
(b) The turbine power output and the thermal efficiency of the OTEC plant.
(c) The mass flow rate of the cold deep seawater required for condensation.

4.1.2. Closed OTEC systems

The other design consists of a closed system OTEC, called Anderson cycle.

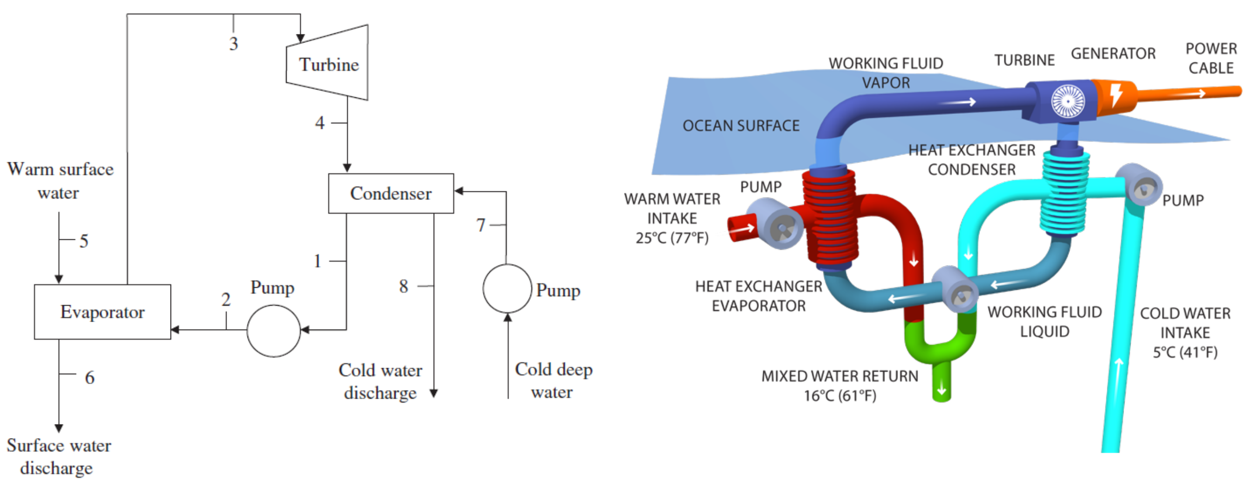


Figure 4.4. Closed Ocean Thermal Energy Conversion (OTEC) system.

This type of cycle needs to use a low boiling point fluid, such as propane or ammonia. The cycle follows the principle of the Rankine cycle, operating between the warm surface temperature and the cold deep-water temperature.
In this case (*wf* for working fluid and *ww* for warm water):

$$\dot{W}_{\text{out}} = \dot{m}_{wf}(h_3 - h_4)$$

$$\dot{Q}_{\text{in}} = \dot{m}_{wf}(h_3 - h_2)$$

But for an ideal heat exchanger we also have:

$$\dot{Q}_{in} = \dot{m}_{ww}(h_5 - h_6)$$

Then;

$$\eta_{th} = \frac{\dot{W}_{out}}{\dot{Q}_{in}} = \frac{\dot{m}_{wf}(h_3 - h_4)}{\dot{m}_{wf}(h_3 - h_2)} = \frac{h_3 - h_4}{h_3 - h_2}$$

Here, the work of the pumps and the power required by the auxiliary equipment are neglected compared to the work of the turbine.

4.2. Wave energy

Wave energy is another form of ocean energy that is also due to solar energy. Waves result from wind that is itself is the result of uneven solar heating of earth and water surfaces.
The interest in producing energy from waves increased since the energy crisis of 1970s. Indeed, wave energy is free and holds a great potential knowing that several millions of waves break into the coast every year.
Extracting ocean energy is still a work in progress since several technological challenges still need to be overcome, including:

Sites of large wave activity are not necessary easily accessible, far from populated and industrial districts and far from power grids.

The equipment required to produce significant power needs to be large and with high mechanical strength.

The effect on marine life still needs to be clearly determined.

Wave heights can reach between 1 m and 5 m (exp: Hawaiian Islands, pacific coast of north America, Scotland, Arabian sea off Pakistan and India).

4.2.1. Power production from waves

For a wave, we can write the relationship between the wavelength (λ) and the period (τ) as:

$$\lambda = 1.56\tau^2$$

A traveling wave can be expressed as:

$$y = a\sin\left(\frac{2\pi}{\lambda}x - \frac{2\pi}{\tau}t\right)$$

Where (y) is the height above mean sea level (in *m*); (a) is the wave amplitude (in *m*) and (t) is time (in *s*).

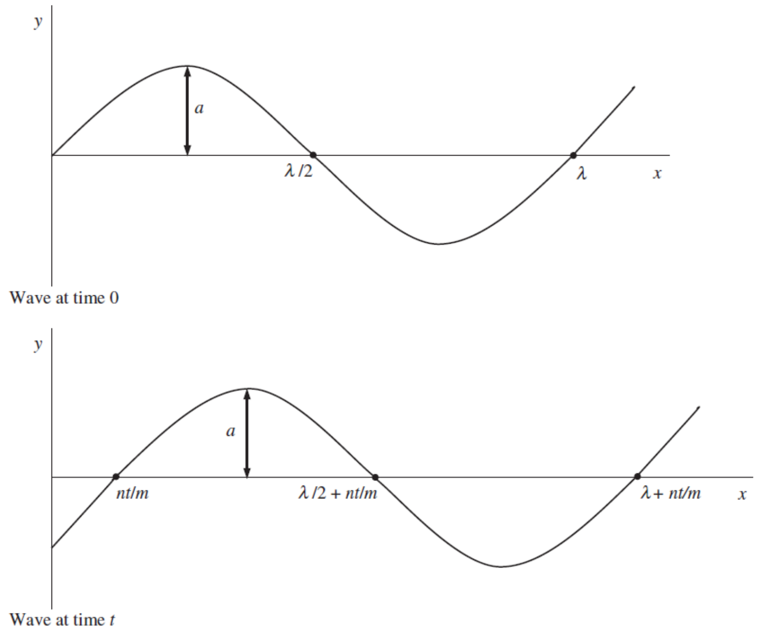


Figure 4.4. A typical traveling wave and its parameters at time 0 and time *t*.

$n = 2\pi/\tau$ Phase rate (s^{-1})

$mx - nt = 2\pi(x/\lambda - t/\tau)$ Phase angle

with

$m = 2\pi/\lambda$

The wave motion in the horizontal direction (x) and the velocity is given by:

$$V = \frac{\lambda}{\tau}$$

Note that water does not flow exactly with the wave. Instead, droplets rotate in place in an elliptical path in the plane of wave propagation with horizontal and vertical semi-axis.

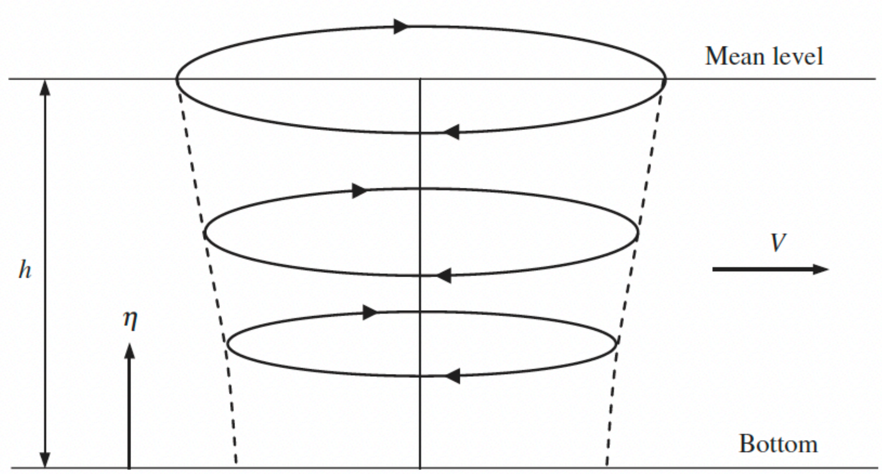


Figure 4.5. Paths of particles at different heights.

The wave has a speed and a height; therefore, it possesses both a kinetic and potential energy:

For a small element $y\,L\,dx$, L is an arbitrary width of the wave and the mean height of $\frac{y}{2}$.
So,

$$d\text{PE} = m\frac{yg}{2} = (\rho yLdx)\frac{yg}{2} = \frac{\rho L}{2}y^2 g\,dx$$

But

$$y = a\sin\left(\frac{2\pi}{\lambda}x - \frac{2\pi}{\tau}t\right) = a\sin(mx - nt)$$

So

$$\int_0^\lambda dP = \int_0^\lambda \frac{\rho La^2}{2}g = sin^2(mx - nt)\,dx = \frac{\rho La^2}{2m}g(\frac{1}{2}mx - \frac{1}{4}\sin\,(2mx))\Big|_0^\lambda = \frac{\rho La^2}{2m}g\left[\frac{m\lambda}{2}\right] = \frac{1}{4}\rho La^2\lambda\, g$$

We can obtain the potential energy (PE) of the wave per unit area by dividing by A=λL, this leads to

$$pe = \frac{PE}{\lambda L} = \frac{1}{4}\rho\, a^2 g$$

We can show following Lamb hydrodynamic theory that the kinetic energy (KE) of the wave per unit area has exactly the same expression as the PE derived above, so

$$ke = \frac{KE}{\lambda L} = \frac{1}{4}\rho\, a^2 g$$

The total energy (potential + kinetic) of the travelling wave is:

Energy of the wave (e_{wave}) = pe+ke = $\frac{1}{4}\rho\, a^2 g + \frac{1}{4}\rho\, a^2 g$

This represents the energy, or work (w), available in the wave in J/m^2. To get the power, we must multiply by the frequency of the wave *f,* leading to:

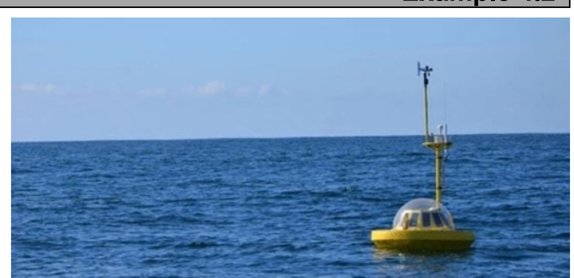
$$\dot{e}_{\text{wave}} = \frac{1}{2}f\rho a^2 g = \frac{1}{2\tau}\rho a^2 g$$

This represents the power available ($\dot{w}$) in the wave in W/m^2.

Example 4.2

An ocean wave off the coast of Tofino, British Columbia, has a height of 3 meters and a period of 5 seconds. The depth of the water at this location is 75 meters. Determine:
(a) The wavelength and the wave velocity.
(b) The work and power potentials per unit area.

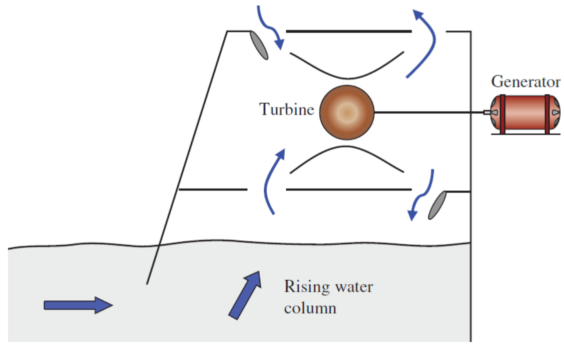
Take the density of seawater to be 1025 kg/m³.



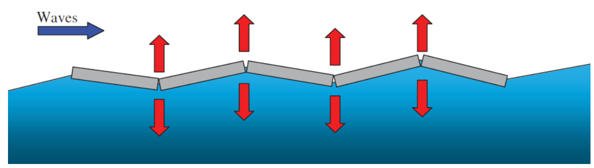
4.2.2. Wave power technologies

Several systems have been developed to capture the energy of the waves and convert them into useful work and electricity.

Oscillating water column technology (OWC)	The main idea behind this technology is to compress the air in column due to the amplitude of the ocean wave. It uses a special turbine (a Wells turbine) that always rotate in the same direction regardless of the direction of the flow.



Pelamis wave energy converter	This consist of five tube sections connected by joints. The structure floats submerged on the surface of the water. The power systems are housed inside each tube joint. A set of hydraulic cylinders resist the water motion and pump fluid into high pressure accumulators. This allows for continuous power generation. Such systems are typically located around 2 to 10 km from the coast. A machine can generate up to 750 kW, but the average production is about 25% to 40% of this. The length is about tube is 3.5 m. The production can go up to 2.7 GWh.



4.3. Tidal energy

Energy can also be harvested from tides. A reservoir can be created with a turbine at the inlet. The motion of water during high and low tides rotates the turbine and generates mechanical energy to be converted to electrical energy. The tidal motion of ocean is due to the gravitational force of the moon and the sun. Tides are different from region to another, from day to day.

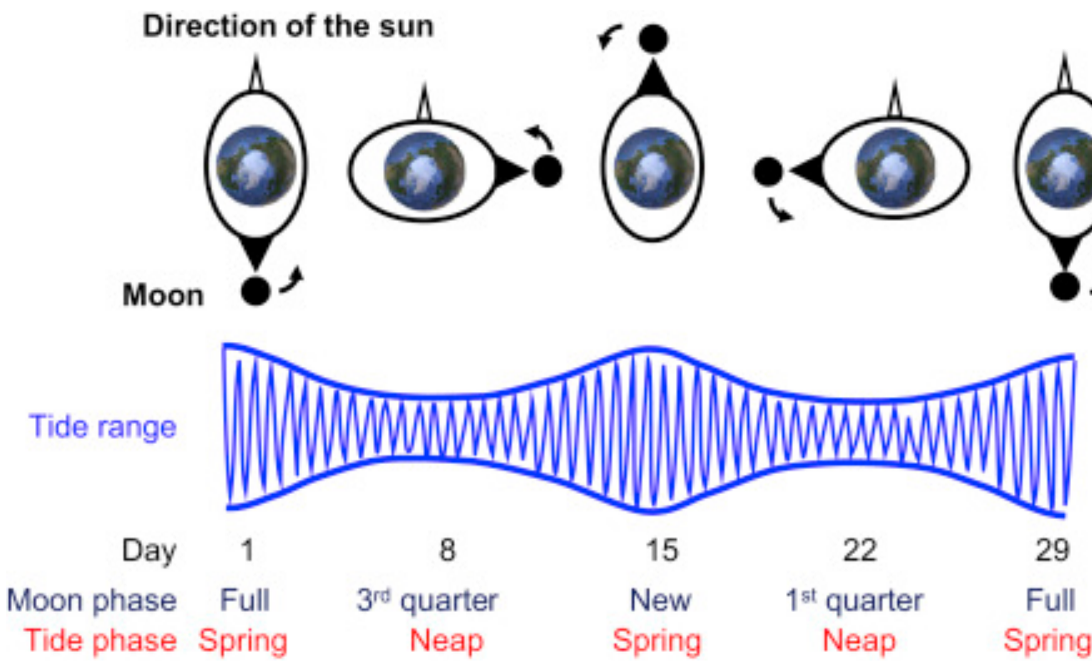


Figure 4.6. Variation of tidal range in a typical lunar month.

The maximum tide occurs during full moons (called spring tide) and is at its lowest during the first and third quarters.
Note that the rotation of the moon around the Earth lasts 24 hours and 50 minutes, and a lunar month lasts 29.5 days.
Some tides can reach up to 10 m. The estimated available tidal power is about 1.5 million MW. Some existing systems can already generate around 240 MW with multiple turbines (e.g., 24 reversible turbines, each with a rated capacity of 10 MW, in the Sihwa Lake Tidal Power Station in South Korea).

4.3.1. Estimation of power potential of tidal energy

Let us consider a single pool tide system (see Figure 4.7) and a small element dm:

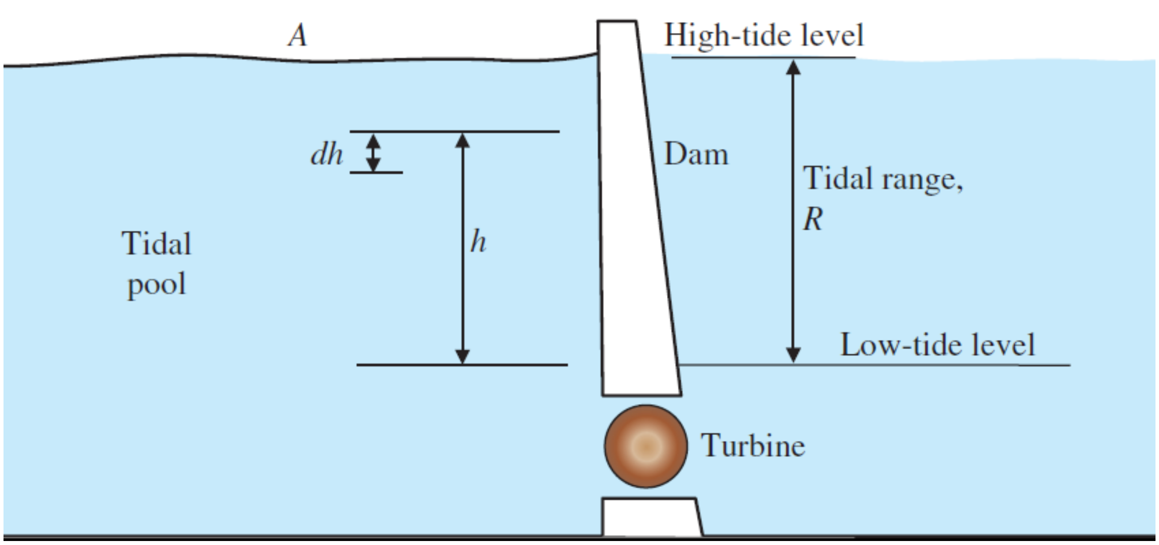


Figure 4.7. A single-pool tidal system for tidal power generation.

$$dW = ghdm$$

With

$$dm = -\rho A dh$$

Here A is the surface of the pool. So:

$$dW = -g\rho A h dh$$

and

$$W = \int_R^0 -g\rho A h\, dh = -g\rho A \int_R^0 h\, dh$$

Here R is the tidal range. This gives an available power (in J) of:

$$W_{\text{available}} = \frac{1}{2} g\rho A R^2$$

This represents the theoretical amount of work that can be generated by tidal energy with a range of R. The power, in W, produced is given then by:

$$\dot{W}_{\text{available}} = \frac{W}{\Delta t} = \frac{1}{2\Delta t} g\rho A R^2$$

Knowing that a tidal cycle lasts 12h and 25 min, so each filling and emptying lasts 6h and 12.5 min or 22350 s, and knowing that the density of sea water is 1025 kg/m^3, then:

$$\dot{W}_{\text{available}} = 0.225 A R^2$$

For example, for a tide of 6 m, the available power per unit area is 8.1 W. This is very low. However, considering a project implemented in the Bay of Fundy with an area of 13,000 km² and an average tidal range of 8 m, this results in a massive power potential of 1.871×10^{11} W or 187,200 MW.
Note, however, that one disadvantage of tidal energy is that it is not continuous, as power production occurs only during the emptying of the tidal pool.
A solution to extend power production is to empty the pool slowly over time. This is called a modulated single-pool tidal system. The available work, in joules (J), in this case, can be written as:

$$W_{\text{available}} = g\rho A R^2 \left\{ 0.988a \left[\cos\left(\frac{\pi t_1}{6.2083}\right) - \cos\left(\frac{\pi t_2}{6.2083}\right) \right] - \frac{a^2}{2}\left(t_2^2 - t_1^2\right) \right\}$$

The value 6.2083 h represents the period of a filling or emptying process of the pool.

The efficiency of a system can computed as:

$$\eta_{tidal} = \frac{\dot{W}_{actual}}{\dot{W}_{available}}$$

This value is typically around 30%.

Example 4.3

A modulated single-pool tidal energy system is proposed for the Bay of Fundy, Nova Scotia, which is known for having the highest tidal range in the world. The system has the following parameters:

- Tidal range: 10 m
- Surface area of the tidal pool: 1 km^2
- Decay parameter (a): 0.08 h^{-1}
- Work production time interval: t_1=1 h to t_2=4 h
- Overall system efficiency: 30%
- Density of seawater: 1025 kg/m^3

Determine:

1. The actual work and power outputs for the modulated single-pool tidal system.
2. The actual work output for the case of a simple single-pool tidal system.