Renewable and Alternative Energies

Topic 3. Ocean energy

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Contents

Topic 3. Ocean energy

- **3.1.** Introduction.
- **3.2.** Wave power.
- **3.3.** Tidal power.
- **3.4.** Ocean thermal energy.

Topic 3. Ocean energy

- **3.1. Introduction**.
- **3.2.** Wave power.
- **3.3.** Tidal power.
- **3.4.** Ocean thermal energy.

3.1. Introduction

- Ocean (marine) energy refers to the **energy derived from oceans or seas**. Oceans cover about 70% of the Earth's surface, making it the **world's largest solar energy collector** and energy storage system.

- Theoretically, 60 million square kilometers of tropical seas absorb an amount of solar radiation that is equivalent to 250 billion barrels of oil per day in terms of energy content.

- This could meet the world's energy requirements many times over, but they are **extremely difficult to harvest** economically for large scale production.

3.1. Introduction

- The energy can be harvested from the ocean **by taking advantage of waves, tidal current, and the thermal gradients** that exist within the body of water. These can be potentially utilized to generate electricity.
- At the **end of 2015**, global ocean energy capacity remained at approximately **530 MW**, mostly in the form of tidal power and, specifically, tidal barrages across bays and estuaries.
- A **commercial market** for ocean energy technology has **not really developed** to date because most technologies are still in various prototype and demonstration stages.

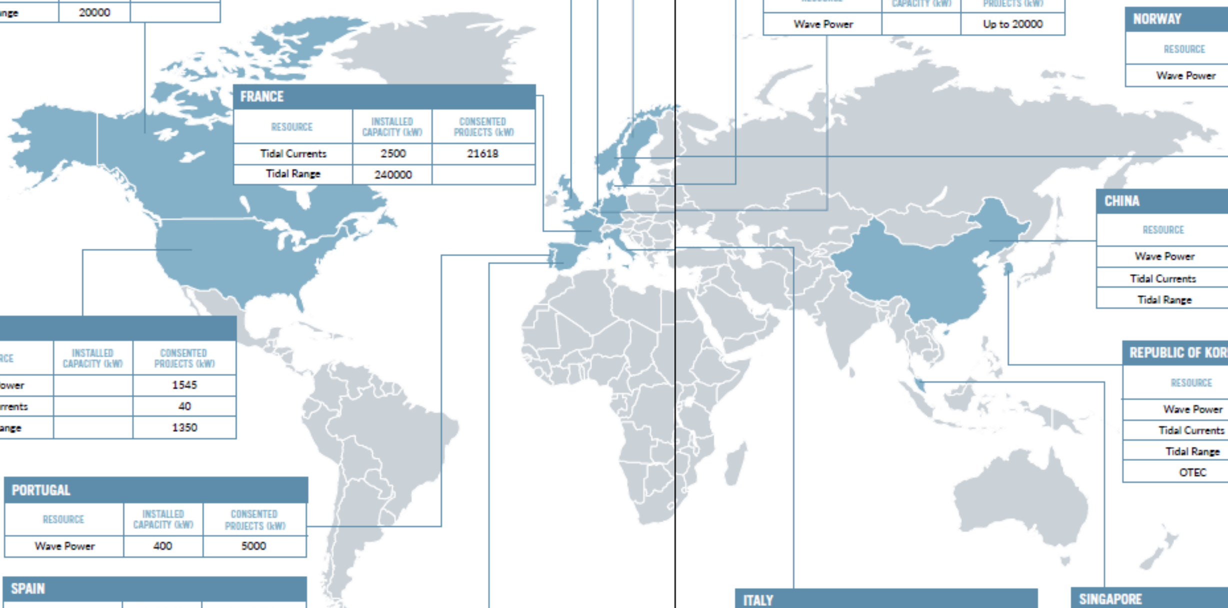
- The one **exception** is the application of established in-stream turbine technology in **tidal barrages**. The two largest ocean energy projects are the 254 MW Sihwa plant in the **Republic of Korea** (completed in 2011) and the 240 MW La Rance tidal power station in **France** (1966), both tidal barrages.

3.1. Introduction

- **Several technologies have been developed** to harvest energy or electricity from oceans that include:
  - **Waves**, derived from the transfer of the kinetic energy of the wind to the upper surface of the ocean.
  - **Tidal range** (tidal rise and fall), derived from the gravitational forces of the Earth-Moon-Sun system.
  - **Tidal currents**, water flow resulting from the filling and emptying of coastal regions as a result of the tidal rise and fall.
  - **Ocean currents**, derived from wind-driven and thermohaline ocean circulation.
  - **Ocean Thermal Energy Conversion (OTEC)**, derived from temperature differences between solar energy stored as heat in upper ocean layers and colder seawater, generally below 1,000 m.
  - **Salinity gradients**, derived from salinity differences between fresh and ocean water at river mouths.

3.1. Introduction

WORLDWIDE OCEAN POWER INSTALLED CAPACITY



NETHERLANDS

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Tidal Currents	1300	1600-2200
Salinity Gradient	50	100000

SWEDEN

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power	200	10400-10600
Tidal Currents	8	

DENMARK

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power		50

UK

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power	960	40000
Tidal Currents	2100	96000

CANADA

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power	9	
Tidal Currents		20450
Tidal Range	20000	

BELGIUM

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power		Up to 20000

NORWAY

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power	200	

FRANCE

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Tidal Currents	2500	21618
Tidal Range	240000	

CHINA

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power	450	2760
Tidal Currents	170	4800
Tidal Range	4100	200

USA

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power		1545
River Currents		40
Tidal Range		1350

REPUBLIC OF KOREA

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power	500	500
Tidal Currents	1000	1000
Tidal Range	254000	254000
OTEC	220	220

PORTUGAL

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power	400	5000

SPAIN

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power	296	

ITALY

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power		99

SINGAPORE

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power	16	
Tidal Currents		50
Tidal Range	5	

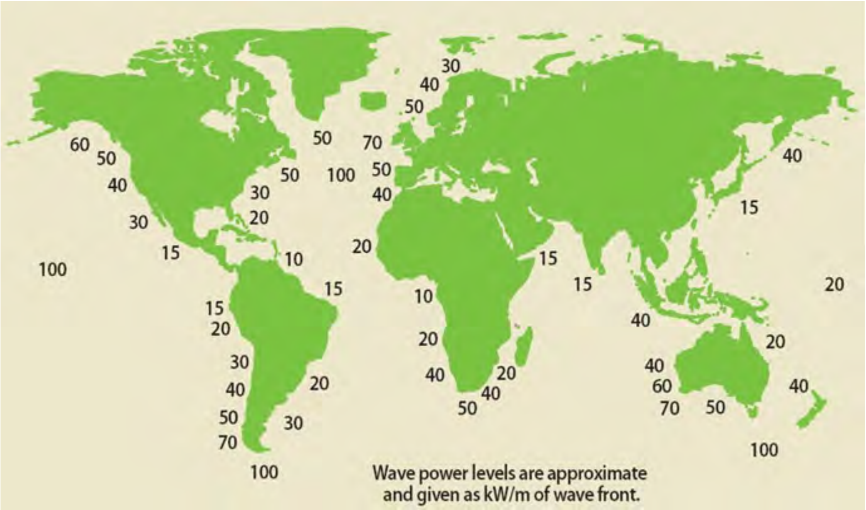
Pablo Castro Alonso

Topic 3. Ocean energy

- **3.1.** Introduction.
- **3.2. Wave power**.
- **3.3.** Tidal power.
- **3.4.** Ocean thermal energy.

3.2. Wave power

- **Wind blowing** over the surface of the ocean **creates waves that can be harvested for energy**.
- In several parts of the world, **ocean waves are fairly consistent** to produce energy on a continuous basis.
- It is estimated that using the current technologies, **about 140-750TWh/year could be generated** economically from wave energy worldwide.
- **Annual average wave power levels (kW/m)** at various parts of the world are **shown in the Figure**.



3.2. Wave power

- Very large energy fluxes can occur in deep water sea waves. **The power in the wave is proportional to the square of the amplitude and to the period of the motion**.

- Therefore the **long period** (~10 s), **large amplitude** (~2 m) **waves have** considerable **interest for power generation**, with energy fluxes commonly averaging between 50 and 70 kW.m^{-1} width of oncoming wave.

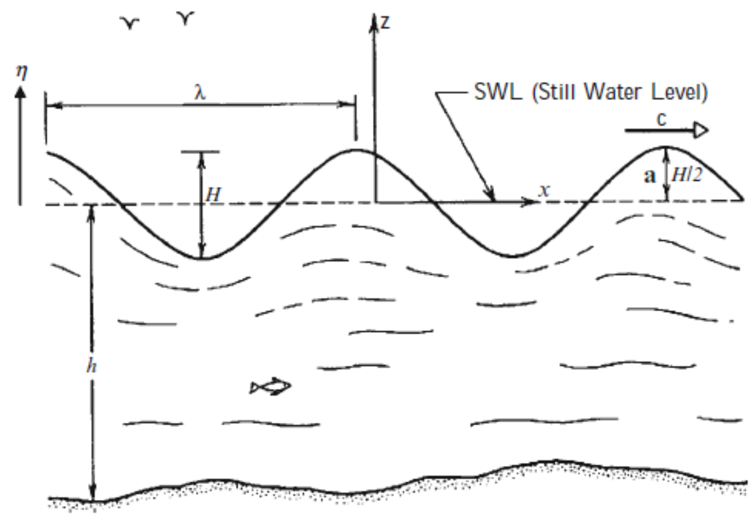
- There are many **difficulties facing wave power developments:**
  - **Wave patterns are irregular** in amplitude, phase and direction. It is difficult to design devices to extract power efficiently over the wide range of variables.
  - There is a **probability of extreme gales or hurricanes** producing waves of freak intensity and the structure of the power devices must be able to withstand ~100 times the power intensity to which they are matched.
  - Wave periods are commonly ~5-10 s (frequency ~0.1 Hz). It is extremely difficult to **couple** this irregular **slow motion to electrical generators** requiring ~500 times greater frequency.

3.2. Wave power

Definitions

- The **water wave motion is periodic and** is **non-linear** in nature. The wave motion is affected by the seafloor characteristics.

- The wave profile is not necessarily a perfect sinusoidal curve but some **approximations and definitions** can be made:
  - Phase velocity, **c**, the velocity of the travelling wave made by the surface motion.
  - Power of the wave, **P**, in terms of the length of the wave (kW/m).
  - Mean water depth, **h**.
  - Wave length, **λ**.
  - Wave height, **H**.
  - Wave amplitude, **a** = H/2.
  - Wave period, **T**.
  - Wave frequency, **w** = 2π/T.
  - Gravity, **g**.



3.2. Wave power

Waves classification

- **Deep-water waves** (h/λ ≥ 0.5).

  For deep-water, it may be assumed that **x → ∞**. The wavelenght, phase velocity and power become:

$$\lambda_{deep-water} = \frac{g*T^2}{2*\pi} \qquad c_{deep-water} = \frac{g*T}{2*\pi} \qquad P = \frac{\rho*g^2*a^2*T}{8*\pi}$$

- **Shallow-water waves** (h/λ ≤ 0.05).

  This suggests that **x → 0**. The shallow-water wavelenght and phase velocity are given by:

$$\lambda_{shallow-water} = T*\sqrt{g*h} \qquad c_{shallow-water} = \sqrt{g*h}$$

- **Intermediate depths** (0.5 ≥ h/λ ≥ 0.05).

  Approximation for wavelenght and celerity does not work. An alternative approximate solution is given below:

$$\lambda_{intermediate-water} = \lambda_{deep-water} * \sqrt{\tanh(2*\pi*h/\ \lambda_{deep-water})}$$

3.2. Wave power

Waves power systems

- Wave power systems **can be installed near shore, offshore, or far offshore**. The design of the energy extraction systems depends on these locations.

- In near shore systems, all the devices are within 20 km of the shore. **Near shore** operations have to consider how the plant will affect the **aesthetic influence** of the area. The **impact on shipping** lane and marine life also requires assessment.

- A **depth greater than 40-50 m** will constitute an **offshore operation**. Even for an offshore operation, the preference is to install all the equipment and control systems at or near the water's surface.

- When installing energy extraction systems, the **orientation of the turbines** to the waves with which they are interacting **should be taken into account**. The electricity production depends heavily on these factors.

3.2. Wave power

Waves power systems

- ***Five basic devices have been proposed or employed for electricity generation from wave energy, and they are:***

  1) Tapered Channel (TAPCHAN).

  2) Oscillating Water Column (OWC).

  3) Point absorber.

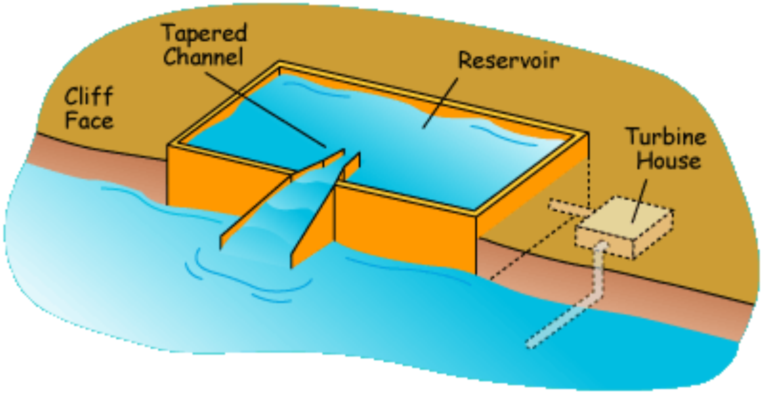
  4) Attenuators.

  5) Overtopping devices.

3.2. Wave power

Waves power systems

1) Tapered Channel (TAPCHAN):



- It is used to **divert water into a reservoir**. These systems, generally, are constructed on a cliff providing a higher water head.

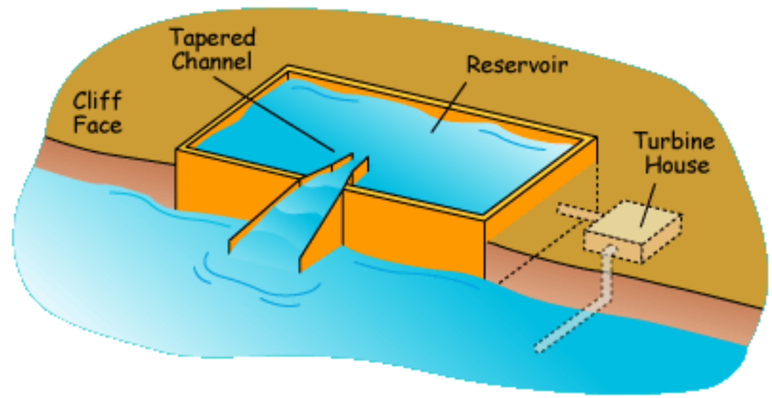
- The **electricity** is **generated using** the same basic concept of **a hydroelectric system**. The reservoir stores the water that is fed through a Kaplan turbine. The narrowing of the channel causes the wave amplitude (wave height) to increase as waves move towards the cliff face, and spill over the walls of the channel and into the reservoir.

- Depending on the wave height, the reservoir can be constructed at higher elevation above mean sea level. **Several meters of water head can be achieved** based on the location of such a system.

3.2. Wave power

Waves power systems

1) Tapered Channel (TAPCHAN):



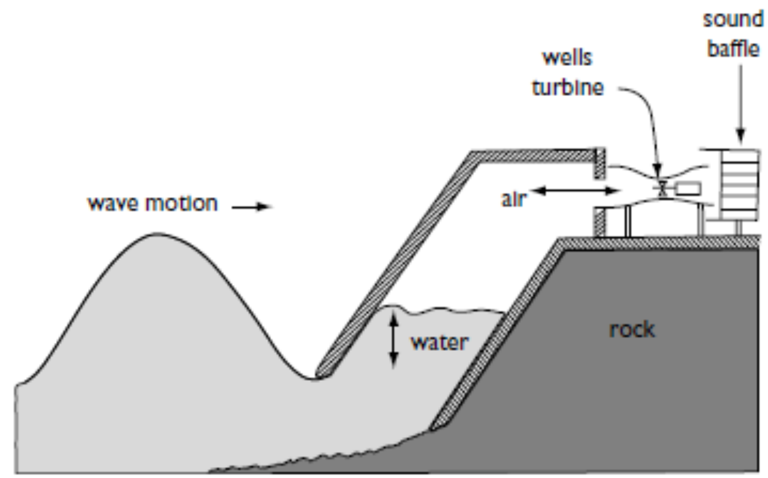
- The **advantages** of TAPCHAN system include:
  - Low maintenance costs.
  - Reliability.
  - Use for the peak load supply.

- The **disadvantages** are:
  - The need for locations with consistent waves.
  - A water head of at least 1 m.
  - A suitable location for a reservoir.

3.2. Wave power

Waves power systems

2) Oscillating Water Column (OWC):



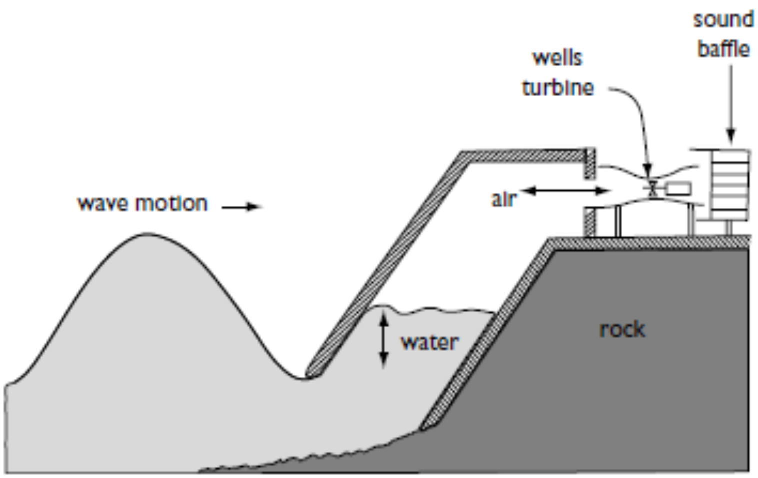
- It operates perpendicular to the direction of wave travel to **capture the power of the wave**.
- These devices are **installed typically onshore or near shore**. Floating types have also been designed for offshore applications.
- In the oscillating water column devices, water enters through a subsurface opening into a chamber that contains a column of air on the top of a column of water. The wave action causes the captured **water column** to rise and fall **like a piston** which in turn **compresses and decompresses the air column**.
- This trapped **air flows** to and from the atmosphere via a turbine causing it **to rotate and generate electricity**.

3.2. Wave power

Waves power systems

2) Oscillating Water Column (OWC):

- The wave pushes the air column through the turbine generating the power. When waves recede, the air column again moves in the opposite direction. The **turbine works in both directions**, and, therefore increases the power production.

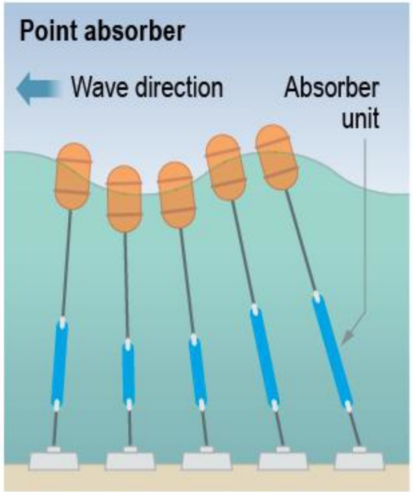


- One of the major challenges is the design of the turbine. To maximize the power generation, **the turbine must rotate in the same direction irrespective of the air flow direction**.

- **Video:** Wave power (Oscillating Water Column).

3.2. Wave power

Waves power systems



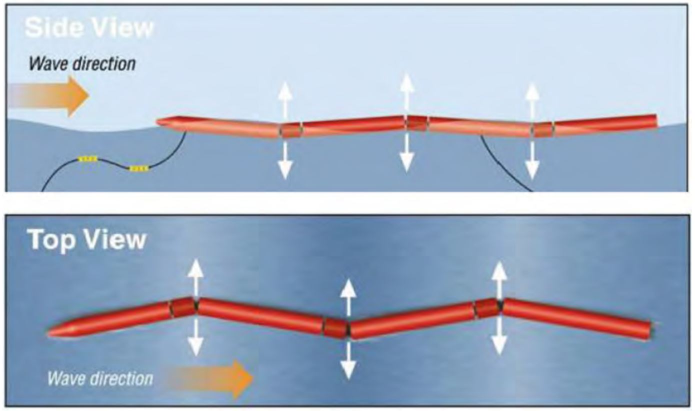
3) Point absorber:

- A point absorber is **a floating device in which a floating buoy moves inside a fixed cylinder due to wave action**. The relative motion is used to drive electromechanical or hydraulic energy converters.
- Currently, the point absorber is **most widely used** as a commercial device **in the USA**. Other challenges with the point absorber are maintaining the structural integrity of the device under extreme wave conditions.
- The buoy or piston **movement must be controlled** so that its motion is in resonance with the waves to maximize energy capture. Also, the piston movement must be limited to keep it within the fixed cylinder.
- A point absorber **can also utilize a bidirectional turbine** to enhance the power output.

3.2. Wave power

Waves power systems

4) Attenuator:

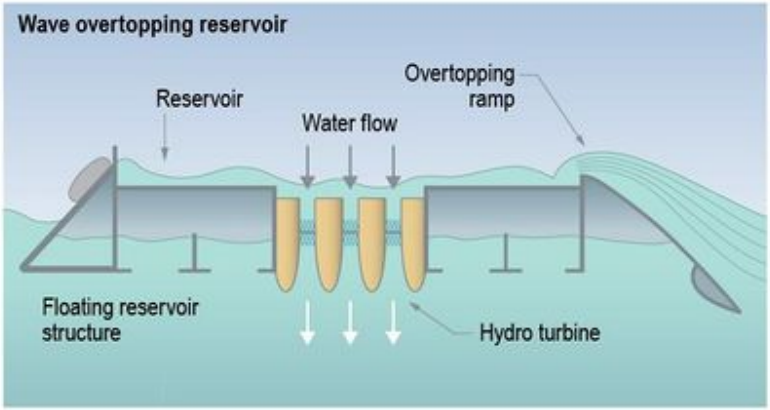


- It is a **long multi-segment floating device** which works in parallel to the wave direction and effectively **rides the waves**.
- Movements along its length are selectively constrained to produce energy. The flexing along the length along the length of the device where the segments connect causes **connected hydraulic pumps or other converters to generate electricity**.
- The **power conversion module is located inside the device** protecting it from water and other harsh environmental conditions. It is fixed slackly to hold it in place.
- **Video:** Wave power (attenuator).

3.2. Wave power

Waves power systems

5) Overtopping devices:



- Overtopping devices have **reservoirs** that are **filled with water** by incoming waves **to levels above the average surrounding ocean**.
- The **water** is then released and is allowed to **fall under gravity through low head hydro-turbines** toward the ocean surface. The energy of the falling water turns hydro-turbines **generating electricity**.
- Overtopping devices have been **designed for both onshore and floating offshore applications**.
- Specially built **seagoing vessels can also capture the energy of offshore waves**. These floating platforms create electricity by funneling waves through internal turbines and then back into the sea.

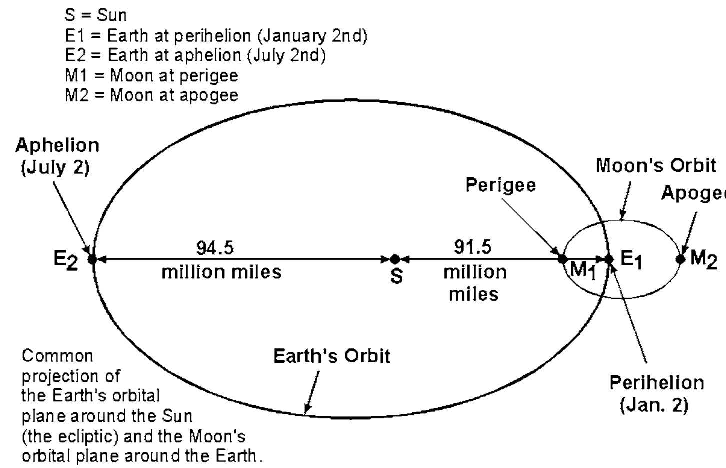
Topic 3. Ocean energy

- **3.1.** Introduction.
- **3.2**. Wave power.
- **3.3. Tidal power**.
- **3.4.** Ocean thermal energy.

3.3. Tidal power

Tidal current energy

- The **tides are cyclic variations in the level of the seas and oceans**. The cyclic variation is predictable, since it is dependent on the position of the Earth and the Moon in their respective orbits.

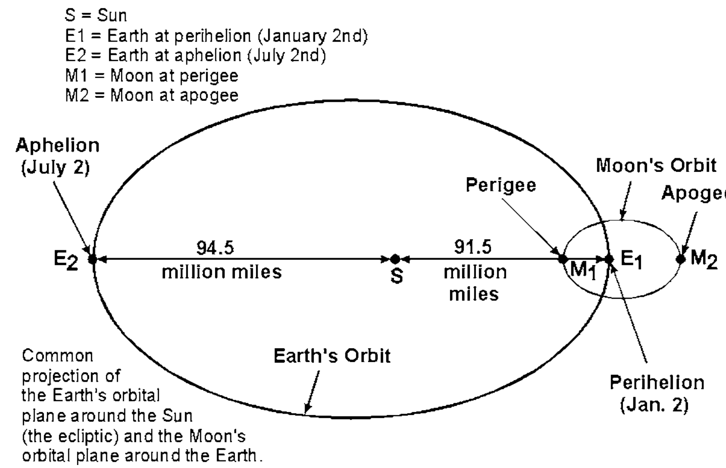


- Various **terminologies associated with tide** and tidal currents are:
  - **Range:** the difference in the height between consecutive high and low tides occurring at a given place. The range is reported in meters or feet.
  - **Spring tide:** the tidal effect of the Sun and the Moon acting in concert twice a month, when the Sun, Earth and Moon are all in a straight line (full Moon or new Moon). The range of tide is larger than average.

3.3. Tidal power

Tidal current energy

- **Neap tide:** this is the opposite of spring tide and occurs when the Moon is at right angles to the Earth-Sun line (first or last quarter). The range of tide is smaller than average.



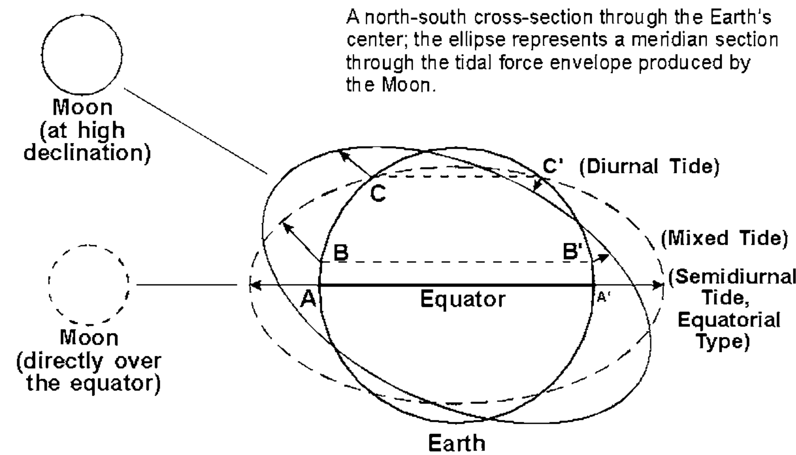
- **Parallax effects:** the distance between the Earth and the Moon varies throughout the month by about 49,879 km. As a result the gravitational pull that causes the tide also varies. During **perigee**, when the Moon is closest to the Earth, above-average ranges in the tides occur. When the Moon is at **apogee**, which is farthest from the Earth, the tidal ranges will be less than average.

- The distance between the Earth and the Sun also varies causing different ranges in the tide. When the Earth is closest to the Sun, called **perihelion**, the tidal ranges increase, and when the Earth is farthest from the Sun (**aphelion**), the tidal ranges will be reduced.

3.3. Tidal power

Tidal current energy

- **Moon's declination affects the types of tide** in any particular location. There are **three daily** cycles of **tide**, called **diurnal**, **semidiurnal**, and **mixed**.
  - **Diurnal tide:** having a period of one tidal day. The tide is said to be diurnal when only one high water and one low water occur during a tidal day (tidal day = 24 h and 50 min).

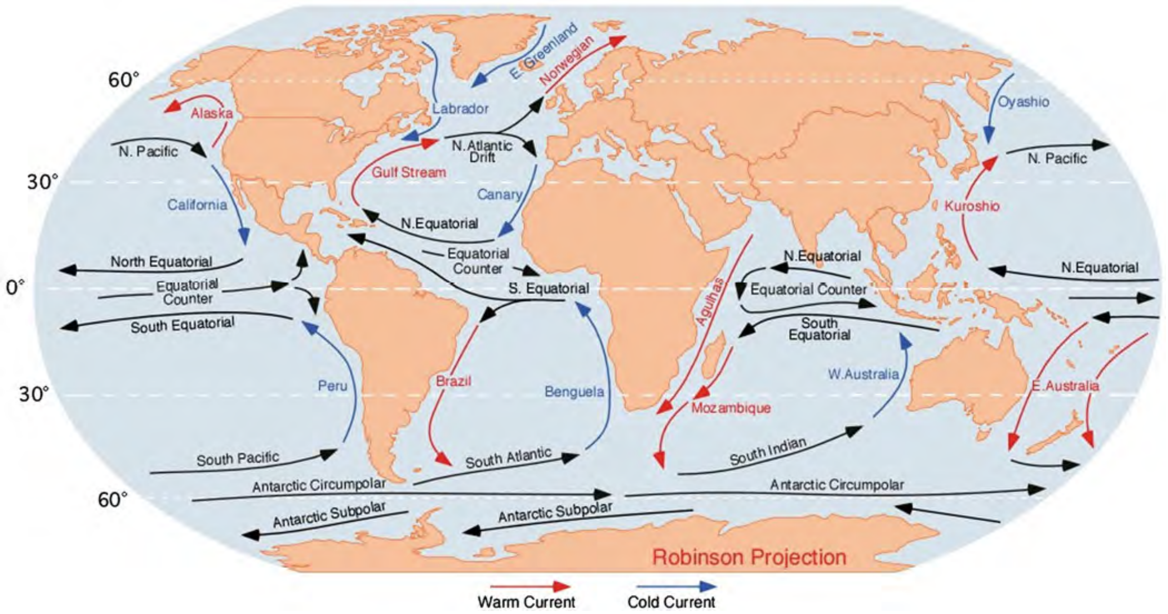


  - **Mixed diurnal:** type of tide characterized by a noticeable diurnal difference in the higher high and lower high waters and/or higher low and lower low waters.
  - **Semidiurnal tide:** having a period of approximately one-half of a tidal day. The predominant type of tide throughout the world is semidiurnal, with two high waters and two low waters each tidal day.

3.3. Tidal power

Tidal current energy

- It is estimated that **3000 GW of tidal energy is available worldwide**, but less than 3% is located in areas suitable for power generation. The total worldwide **power in ocean currents** has been estimated to be about **5000 GW**.
- The **potential for installation** of marine current turbines **in Europe** is estimated to be **12000 MW**.



3.3. Tidal power

Tidal power technologies

Tidal power technologies may be categorized into two groups as follows:

1) Tidal barrage method.

2) Tidal turbine method.

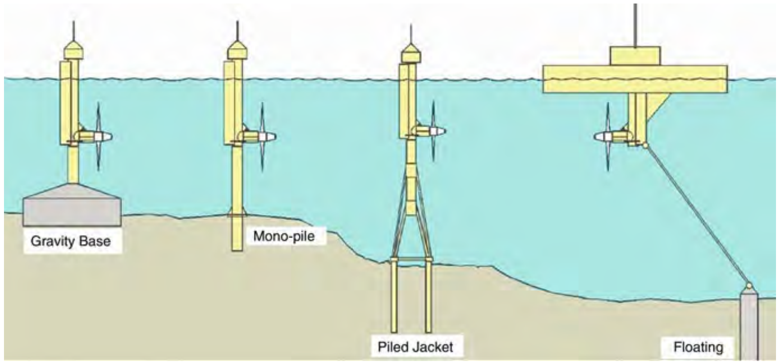
1) Tidal barrage method:

- A barrage or dam is typically used to **force the water** during high tide **into a reservoir**. When the tides produce an adequate difference in the level of the water on the opposite side of the dam, the gates are opened.
- The water is allowed to flow through a low head turbine, in a **similar manner as a hydroelectric system**. Gates and turbines are installed along the dam. The turbines turn an electric generator to produce electricity.
- There are **currently several commercial barrages** in operation. The main ones are located in La Rance, France, in the Republic of Korea and in Annapolis Royal, Nova Scotia, Canada.

3.3. Tidal power

Tidal power technologies

2) Tidal turbine method:



- Among various technological options, the **use of tidal currents to run the turbines appears to be the best option**. A number of countries are interested in pursuing the use of ocean current energy technologies.
- The technology is **at an early stage of development**, with only a small number of prototypes and demonstration units having been tested to date.
- The **main issue** with the tidal current system **is the design of the turbine**. Most of the designs involve submerged systems.
- Although the tide turbines look the same as wind turbines, their working principle is different. Submerged **tide turbines capture energy by the processes of hydrodynamic, rather than aerodynamic lift or drag**.

3.3. Tidal power

Tidal power technologies

2) Tidal turbine method:

- These **turbines** have rotor blades, **a generator** for converting the rotational energy into electricity, and a means for transporting the electrical current to shore for incorporation into the electrical grid.

- **Four types of turbine** have been explored for generating electricity from the tidal current, and these include:
  - *Horizontal axis turbines:* similar to wind turbines. The power output depends on the rotor diameter and the stream flow rate and can be controlled using pitch controlled blades.

    Video: Tidal horizontal turbine.
  - *Vertical axis turbines:* in vertical axis turbines, water stream flow is perpendicular to the rotational axis of the turbine. Several vertical axis turbines have been designed for their feasibility in commercial applications.

    Video: Tidal vertical turbine.

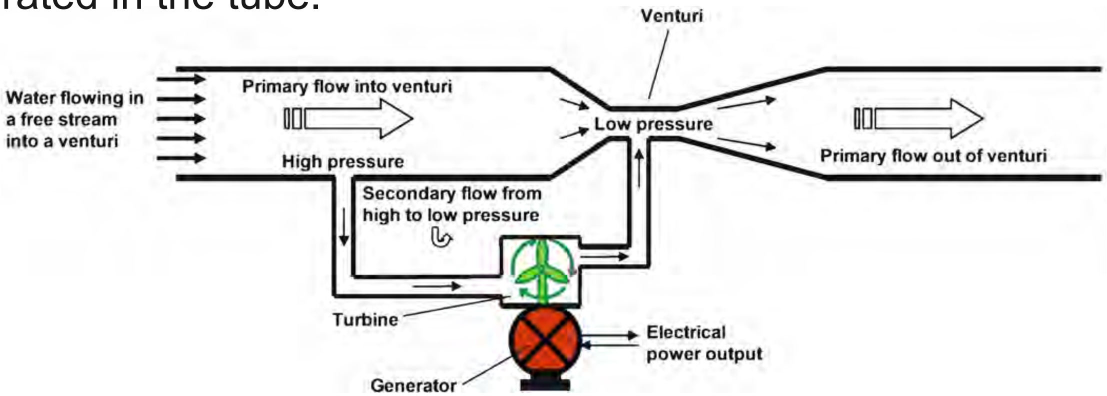
3.3. Tidal power

Tidal power technologies

2) Tidal turbine method:

– *Linear lift mechanism:* a large wing-like hydroplane moves up and down in a linear motion and compresses the oil in a hydraulic ram to run a hydraulic power converter.

– *Venturi based systems:* a venturi tube is used to accelerate the water flow. As the water is accelerated through the tube due to the reduction in cross-sectional area, a pressure drop is generated in the tube.



Topic 3. Ocean energy

- **3.1.** Introduction.
- **3.2**. Wave power.
- **3.3.** Tidal power.
- **3.4. Ocean thermal energy**.

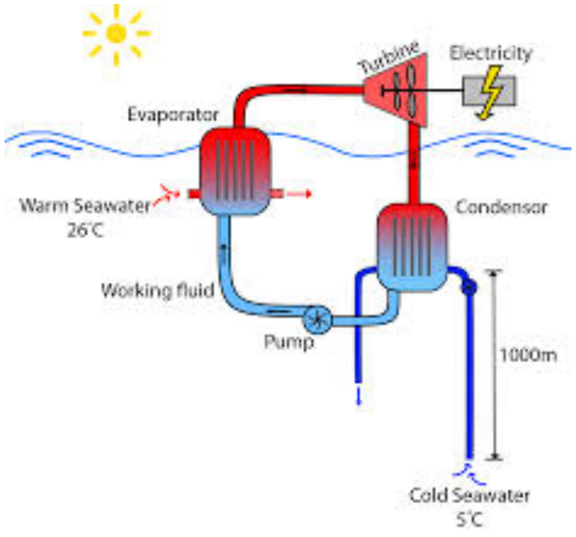
3.4. Ocean thermal energy

- **Solar energy stored** in the ocean water **is converted to electric power by** using **Ocean Thermal Energy Conversion (OTEC)** technology **which utilizes the ocean's natural thermal gradient**.

- The **ocean's layers of water have different temperatures. A thermodynamic cycle could be operated between this temperature difference** to drive a power-producing cycle.

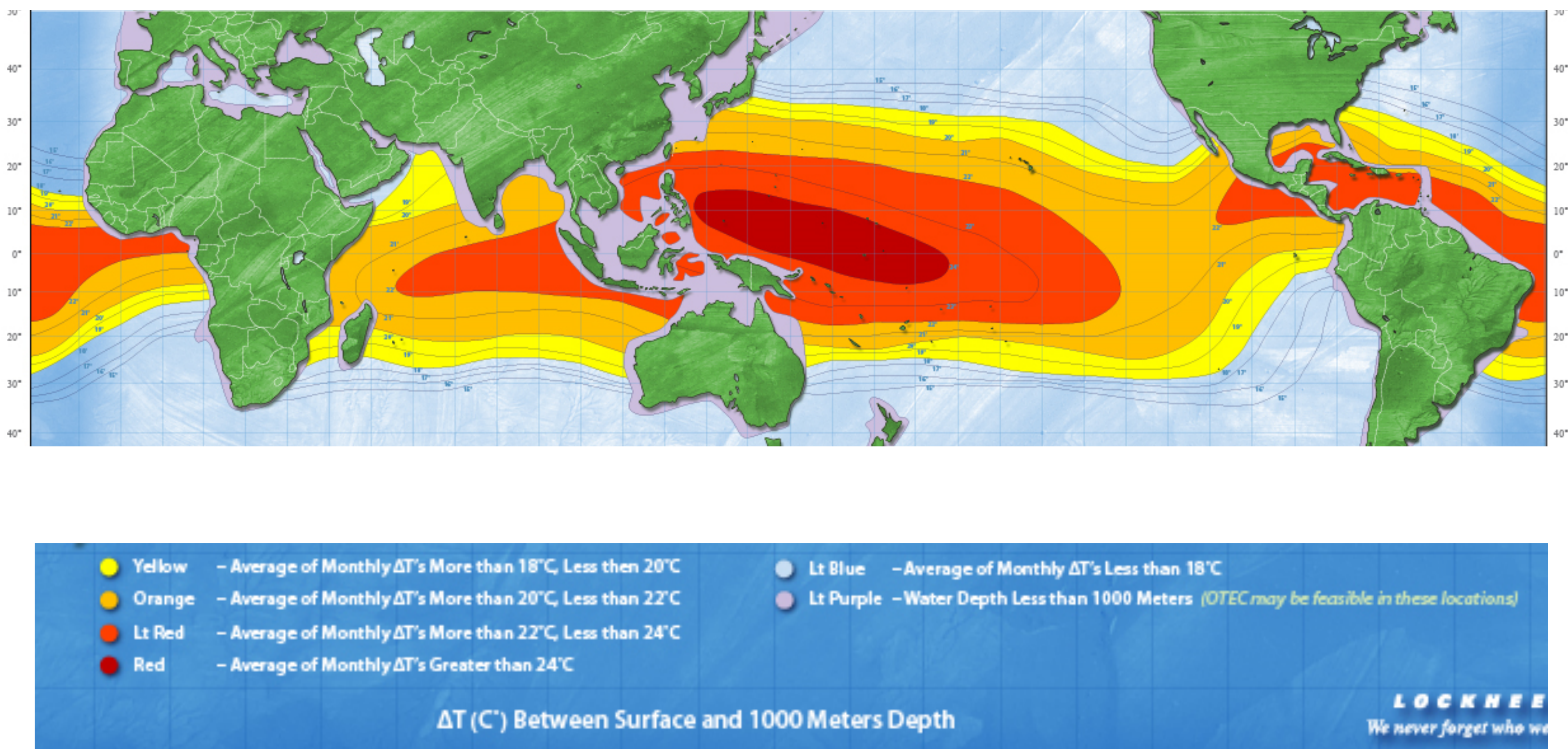
- **A temperature difference of about 20°C** between the warm surface water and the cold deep water is desirable **for an OTEC** system to produce a significant amount of power.

- **Video:** Ocean Thermal Energy Conversion (OTEC).



3.4. Ocean thermal energy

- The temperature gradient at various parts of the world is shown in the Figure. As can be seen, a **temperature gradient of 20°C exists in tropical coastal areas**, roughly between the Tropic of Capricorn and the Tropic of Cancer.



3.4. Ocean thermal energy

Ocean thermal generation has the following advantages and disadvantages

- **Advantages:**
  - The energy is free - no fuel is needed and no waste is produced.
  - Not expensive to operate and maintain.
  - Can produce a significant amount of energy.
- **Disadvantages:**
  - Variable energy supply but more consistent than wind or solar energy.
  - Needs a suitable site, where waves or currents are consistently strong.
  - Must be able to withstand very rough weather.
  - Costly to develop.
  - Visual impact if turbines are above water or on shore.
  - Can disturb or disrupt marine life - including changes in the distribution and types of marine life near the shore.
  - Poses a possible threat to navigation from collisions.
  - May interfere with mooring and anchorage lines with commercial fishing.
  - May degrade scenic ocean front views from wave energy devices located near or on the shore, and from onshore overhead electric transmission lines.

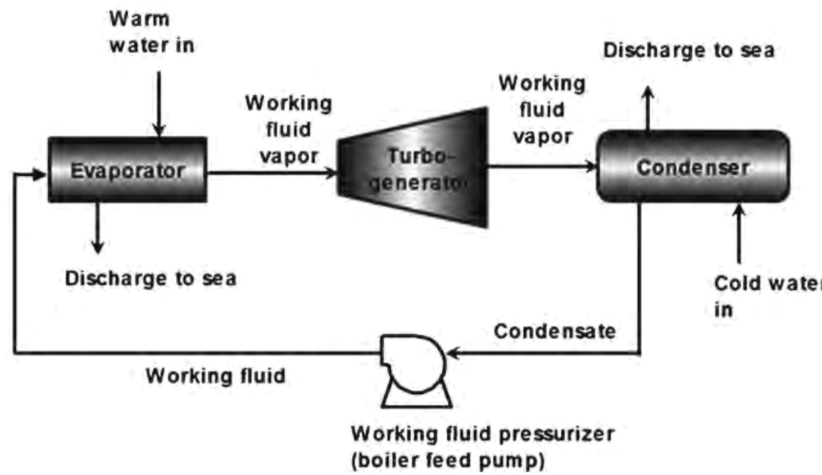
3.4. Ocean thermal energy

Three basic OTEC system designs have been demonstrated to generate electricity. These are:

1) Closed cycle.

2) Open cycle.

3) Hybrid cycle.



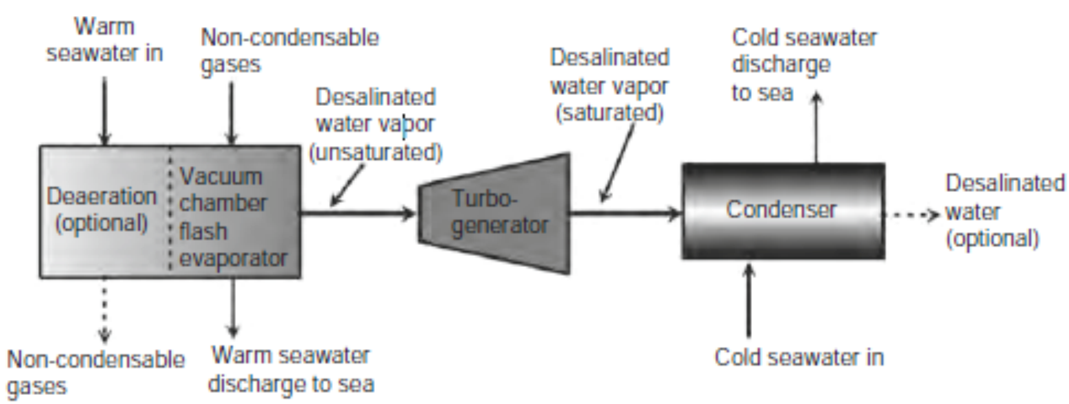
1) Closed cycle:

- In a closed-cycle OTEC system, **warm seawater vaporizes a working fluid, such as ammonia, flowing through a heat exchanger (evaporator)**. The vapor expands at a moderate pressure and turns a turbine coupled to a generator that produces electricity.
- The **vapor is then condensed in another heat exchanger (condenser)** using cold seawater pumped from a certain depth of the ocean through a cold-water pipe.
- The condensed working fluid is pumped back to the evaporator to repeat the cycle. The **working fluid remains in a closed system and circulates continuously**.

3.4. Ocean thermal energy

2) Open cycle:

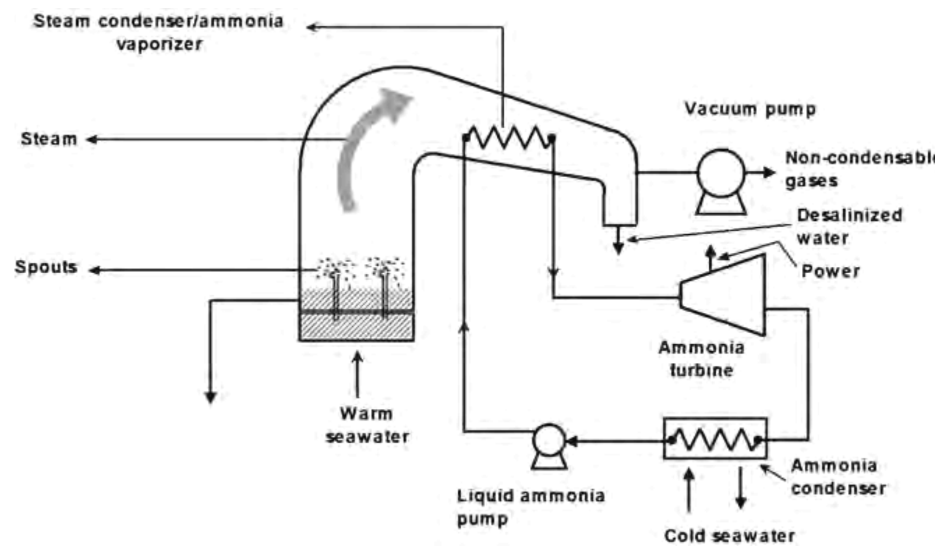
- In an open-cycle OTEC system, **warm seawater is the working fluid**. The warm seawater **is "flash" evaporated in a vacuum chamber to produce steam** at an absolute pressure of about 2.4 kilopascals (kPa).
- The **steam expands through a low-pressure turbine that is coupled to a generator to produce electricity**. The steam exiting the turbine is condensed by cold seawater pumped from the ocean's depths through a cold-water pipe.
- **If a surface condenser is used in the system**, the condensed steam remains separated from the cold seawater and **provides a supply of desalinated water**.



3.4. Ocean thermal energy

3) Hybrid cycle:

- A hybrid cycle **combines the features of both the closed-cycle and open-cycle** systems. In a hybrid OTEC system, **warm seawater enters a vacuum chamber where it is flash-evaporated into steam**, which is similar to the open-cycle evaporation process.
- The **steam vaporizes the working fluid of a closed-cycle loop on the other side of an ammonia vaporizer**. The vaporized fluid then drives a turbine to generate electricity. The steam condenses within the heat exchanger and provides desalinated water.



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