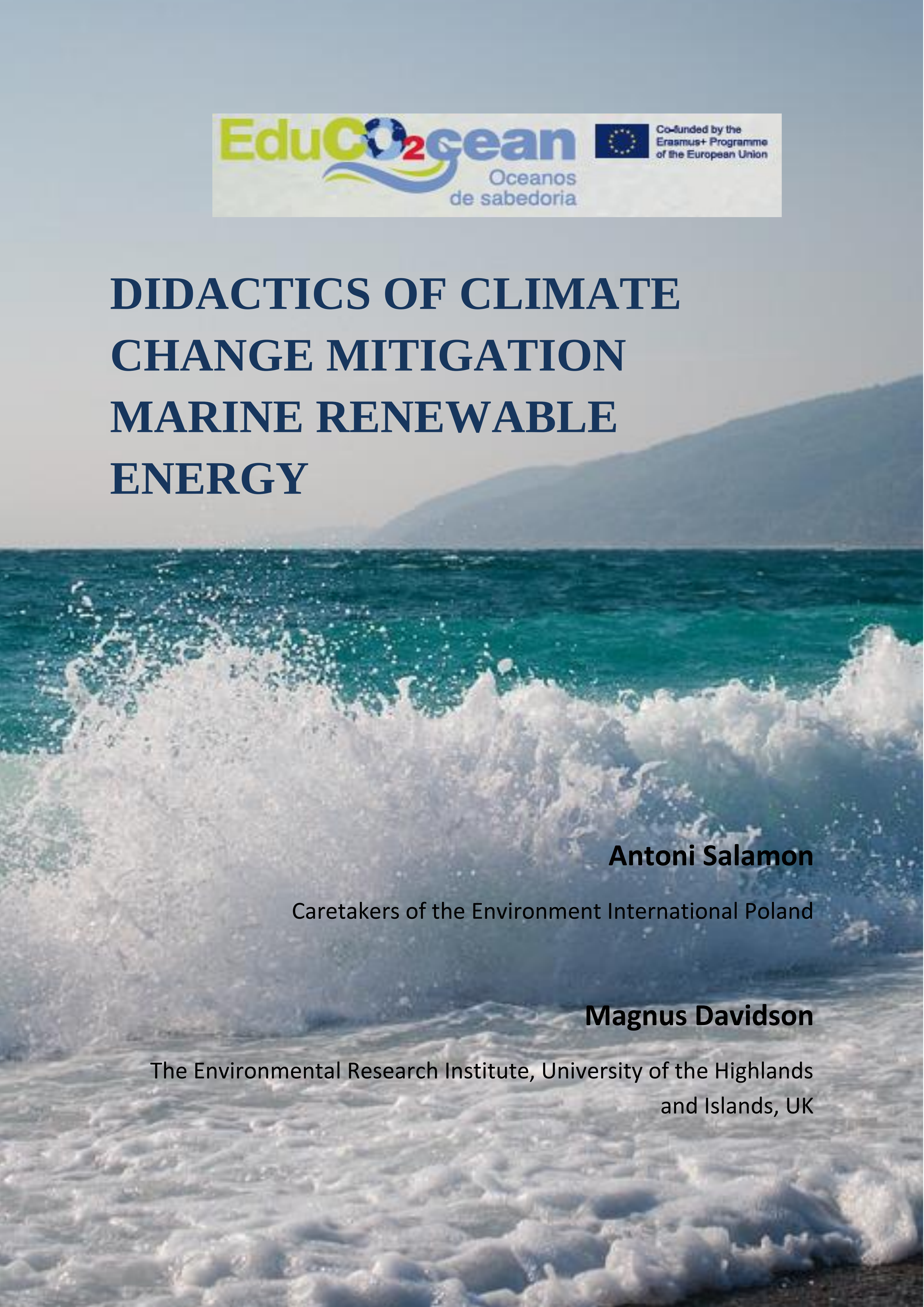

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Co-funded by the Erasmus+ Programme of the European Union

DIDACTICS OF CLIMATE CHANGE MITIGATION MARINE RENEWABLE ENERGY

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KEY WORDS:

Wave energy
Tidal energy
Osmotic power
Wave resources
Tidal resources

Wave technology

Tidal technology

Carbon mitigation

Climate change

Index

INTRODUCTION

In a world experiencing a rapid population growth and the development depending on the technology, securing save and liable power sources is one of this century great challenges.

Currently, most of the energy is obtained by burning fossil fuels, paying for that a high price in the form of unfavorable climate change caused by greenhouse effect related to the emission of gigantic amounts of CO_2 to the atmosphere. According to reports of the IPCC (Intergovernmental Panel on Climate Change, established by the United Nations in 1988), the current climate change already have and will have disastrous consequences in the future, not only for the inhabitants, but in general for life on Earth.

How to counteract this? Curbing dangerous climate change requires very deep cuts in emissions, as well as the use of alternatives to fossil fuels worldwide, replacing them with renewable energy sources as soon as possible. If we want to avoid the transformation of our planet to conditions that have not existed for millions of years, the simplest and most sensible solution is to stop the increase in greenhouse gases (GHG) in the atmosphere by reducing their emissions. There is no single magic way and only the right path - to do this in a sensible time counted in decades, one should apply the entire portfolio of different solutions (renewable energy, nuclear energy, cogeneration, improving the efficiency of energy production and consumption, carbon sequestration, changes in consumer behavior etc.), some of which are as accessible as possible, some are within easy reach, and some will require many years of research.

One of the possibilities is ocean energy - marine energy, renewable energy with zero GHG emission available in many places around the world. It is a source of energy with enormous potential: the UN report estimates that the total ocean energy is higher than the total electric energy produced worldwide in 2008 and is renewed every day.

Marine energy can be defined as energy derived from technologies that utilize seawater as their motive power or harness the water's chemical or heat potential.

Let's not forget that the largest component of ocean energy it is heat energy. The estimated value of thermal energy accumulated in the ocean is 44,000 TWh, according to IPCC data. However, the heat of the ocean is currently not considered as a source of energy, although the technology that enables it is widely known.

The possible renewable resource in the ocean comes from six distinct sources, each with different origins and requiring different technologies for conversion:

- Wave
- Tidal range
- Tidal stream
- Ocean current
- Salinity gradient
- Thermal gradient

All marine energy technologies, except tidal barrages and a singular other cases, are conceptual, undergoing research and development, or are in the pre-commercial prototype and demonstration stage. Currently, more than 100 different marine energy technologies are under development in over 30 countries.

In this didactic unit we will find an explanation of physical processes related to the formation of waves or tides and the discussion of the principles of operation of a given technology. Tidal stream technology can be used also to draw energy from ocean currents. Very promising perspectives of osmotic power will be also discussed.


Workbook activities


Laboratory experiments


Field Activities


School Science and Society

INITIAL QUESTIONS

Answer what you know before starting the study:

1. **What is marine energy?**
2. **What causes waves?**
3. **How to draw energy from the waves?**
4. **Where are the tides coming from?**
5. **How to harness tides to generate electricity?**
6. **What is the impact of using marine energy on environment and carbon mitigation?**

CONCEPTS

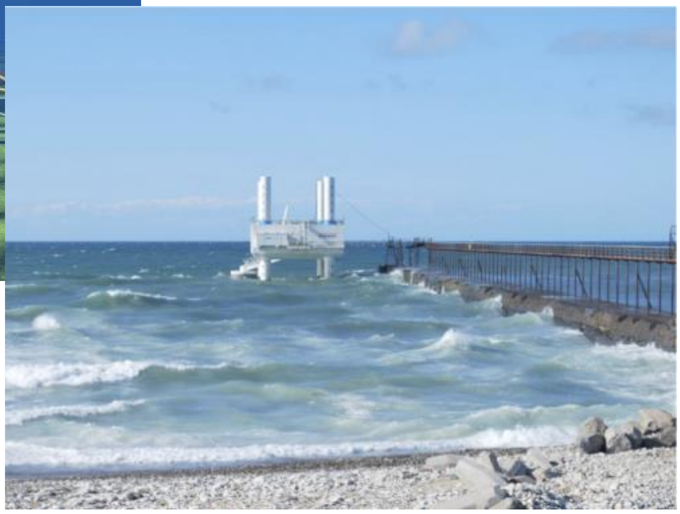
- Ocean as a global source of clean energy.
- Wind generate waves.
- Wave energy is an available source of energy.
- Gravity and orbital motion of the Earth, Sun and the Moon creating tides.
- Tides - an inexhaustible source of clean energy.
- Marine energy mitigates climate change.
- The use of marine energy reduces environmental costs in the energy production process.

OBJECTIVES

- To discover the ocean as a future source of energy.
- To identify the types of energy contained in the ocean.
- To understand the wave formation process.
- To get to know the most effective wave energy technologies.
- To understand creation of tides.
- To recognize the energy availability from wave and tidal around the globe.
- To get acquainted with the currently used and planned technologies of the use of tidal energy.
- To recognize the possibilities of mitigating climate change using marine energy.
- To recognize environmental costs related to technologies that use marine energy.

UNITS

1 What is marine energy?



With the global ocean covering over 70% of the Earth's surface, it is the world's largest collector and retainer of the sun's vast energy – and the largest powerhouse in the world. The ocean absorbs solar energy, exchanges energy with the atmosphere, distributes heat and cold all over the globe. Ocean is water, so if any force acts on it, it will move. Thus, ocean waters are also huge source of kinetic energy to be used. The forces acting on ocean waters have different origin: wind, gravity, temperature gradient, salinity gradient, and atmospheric pressure differences.

Marine energy, due to the above various origins of this energy and technologies used, can be generally divided into: wave energy, tidal energy, ocean currents. The latest scientific discoveries allow one more item to be added to this list: the osmotic power.

Wave energy

Waves are generated by wind. Wind comes from solar energy. Waves gather, store, and transmit this energy thousands of miles with little loss. As long as the sun shines, wave energy will never be depleted. It varies in intensity, but it is available twenty-four hours a day, 365 days a year. Waves are present in all places of the ocean where the wind blows.

They hide huge energy potential, estimated at 32,000 TWh per year, according to IPCC data. Figure 1 shows what power, expressed in kilowatts per meter of length, is carrying by waves at different points of the globe.

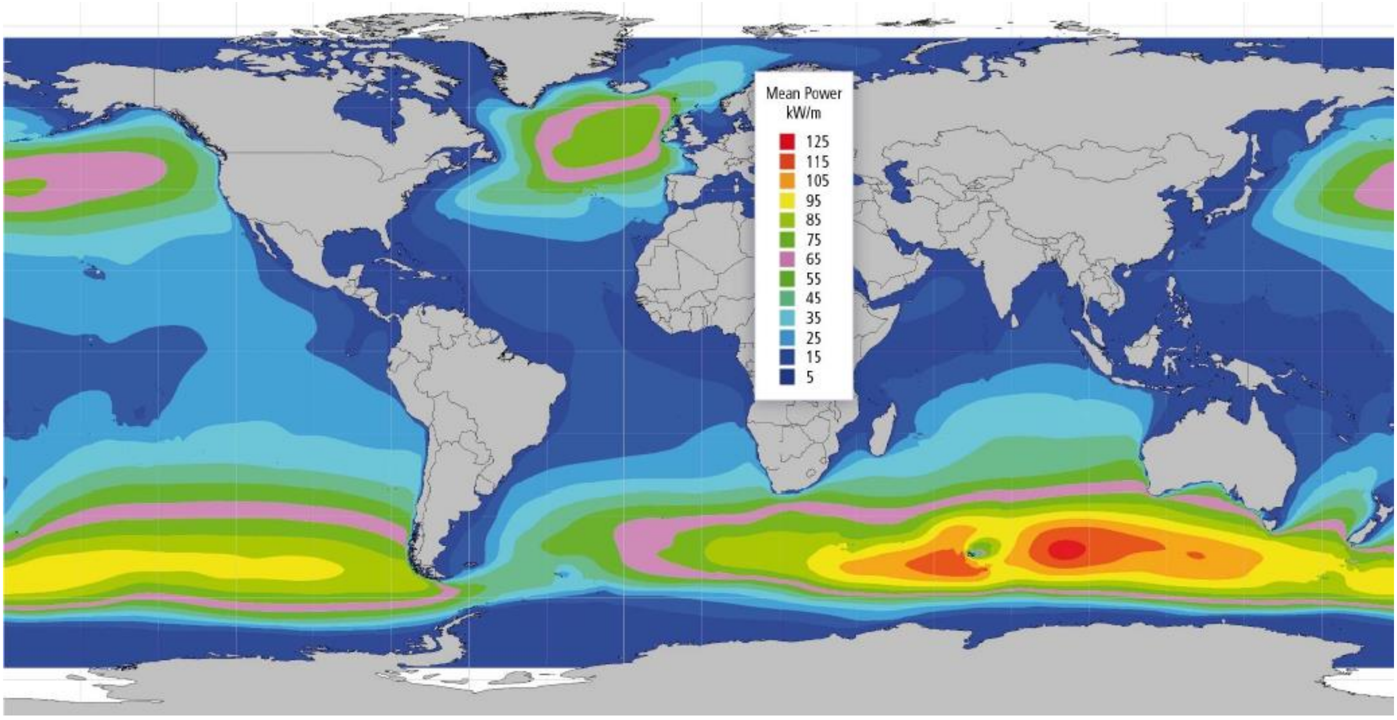


Figure 1: Wave power distribution. Source: report IPCC 2012

Tidal energy

According to definition given by Morrison and Owen, *"A tide is a distortion in the shape of one body induced by the gravitational pull of another nearby object".* The tides on ocean are cyclical changes of the sea level, rises and falls, caused by the combined effects of gravitational forces exerted by Moon and Sun and the orbital motion of Earth in reference to Sun and Moon.

The tides are everywhere, usually twice daily, every day, regardless of whether it is day or night, whether the sky is cloudy or the sun is shining, whether the wind is blowing or not, whether it is summer or winter, predictable on hundreds years forward. They take place on every water resevoir, even in the cup of tea, but effect is microscopic.

From an energetic point of view, it is important how high the tide is and how much water it raises. In the middle of the ocean, the tides are small, several or several dozen centimeters. The situation is different close to the coast. The height of the tide very strongly depends on the topography of the shoreline, the depth of the sea and the shape of the seabed.

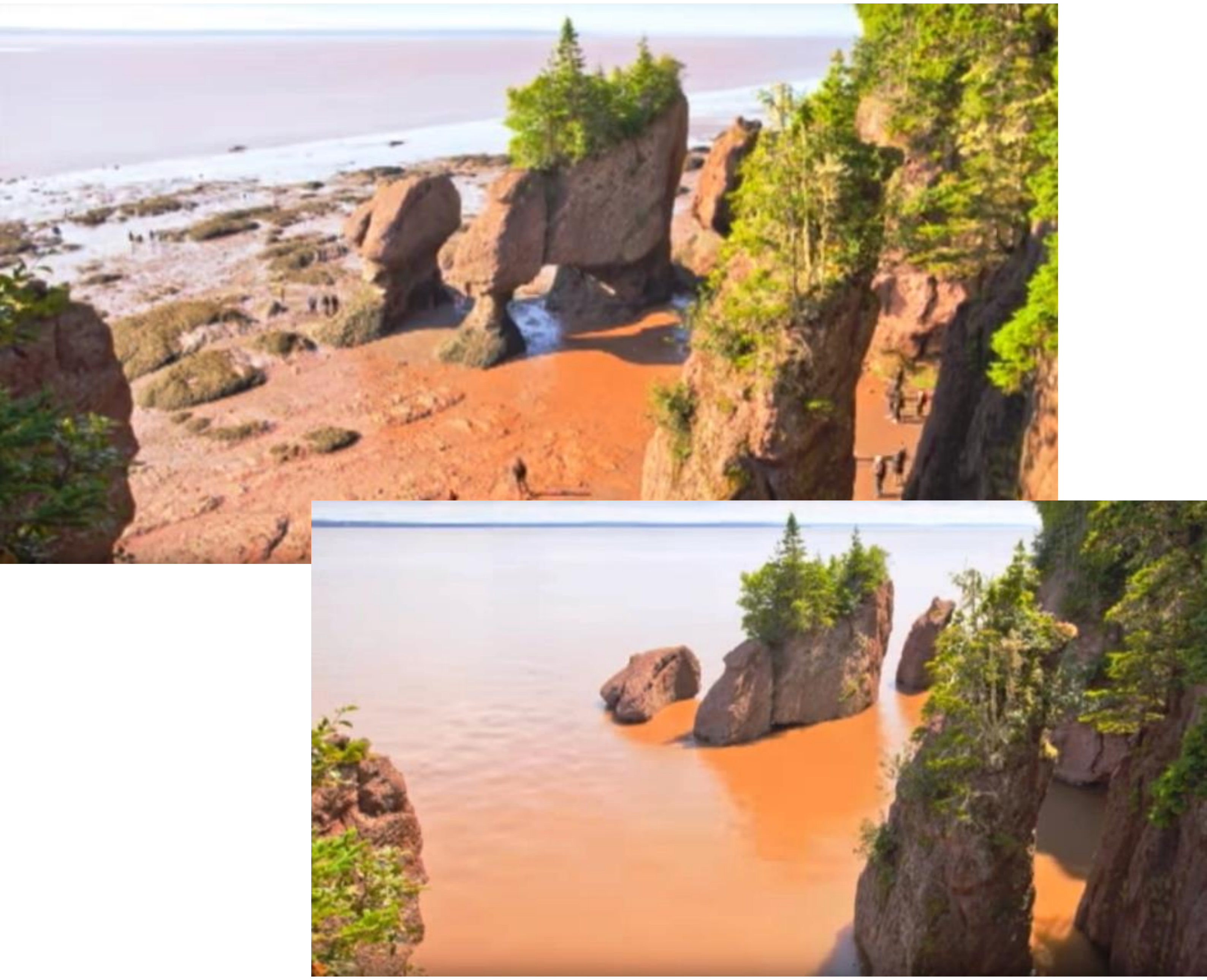


Figure 2: Low and high Tide in Hopewell Rocks, Bay of Foundy, Canada

Figure 3 - Bay of Fundy at High Tide, photo by NASA
Source: NASA – MODIS (Moderate Resolution Imaging Spectroradiometer)

Figure 4 - Bay of Fundy at Low Tide, Google Map.

The record tides of the order of 17m are listed in the Bay of Fundy, Canada. As estimated to Bay of Funds flows in and flows out 200 billion tons of water, twice in each lunar day. This is a potentially giant energy source that we can theoretically use four times a day.

Theoretical global tidal power potential is in the range of 1 to 3 TW (Report IPCC 2012).

Salinity gradient energy

Salinity gradient energy (also called osmotic power), arising from differing salt concentrations, as occurs where a river empties into an ocean. Demonstration projects use "pressure retarded osmosis", with freshwater flowing through a membrane to increase the pressure in a tank of saltwater. Pressurized liquid can drive a turbine. Expensive technology, is not further developed.

Another demonstration project use "reverse electro dialysis" with ions of salt passing through a specific membrane. More specifically, it is energy generated by a natural phenomenon occurring when fresh water comes into contact with seawater through a nano pore membrane.

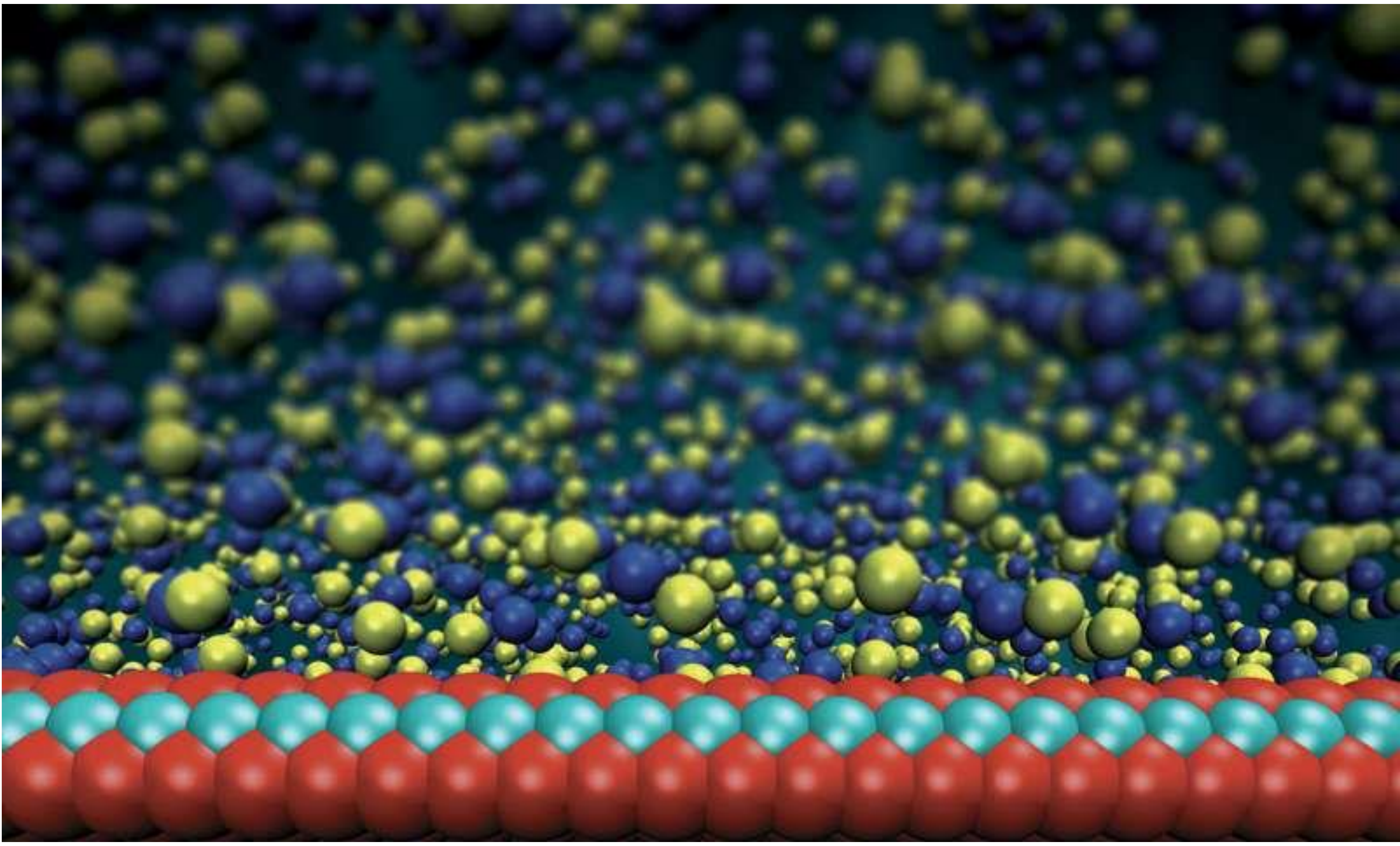


Figure 5 - Three-atoms thick membrane.

Researchers at the Laboratory of Nanoscale Biology of Ecole Polytechnique Federale de Lausanne, have developed an osmotic power generation system that delivers never-before-seen yields. Their innovation lies in a three atoms thick membrane used to separate the two fluids. Such a membrane has nano pores, a holes of the order of 1 billionth of a meter.

As we can read in EPFL's article *ELECTRICITY GENERATED WITH WATER, SALT AND A THREE-ATOMS THICK MEMBRANE:* The concept is fairly simple. A semipermeable membrane separates two fluids with different salt concentrations. Salt ions travel through the membrane until the salt concentrations in the two fluids reach equilibrium. That phenomenon is precisely osmosis.

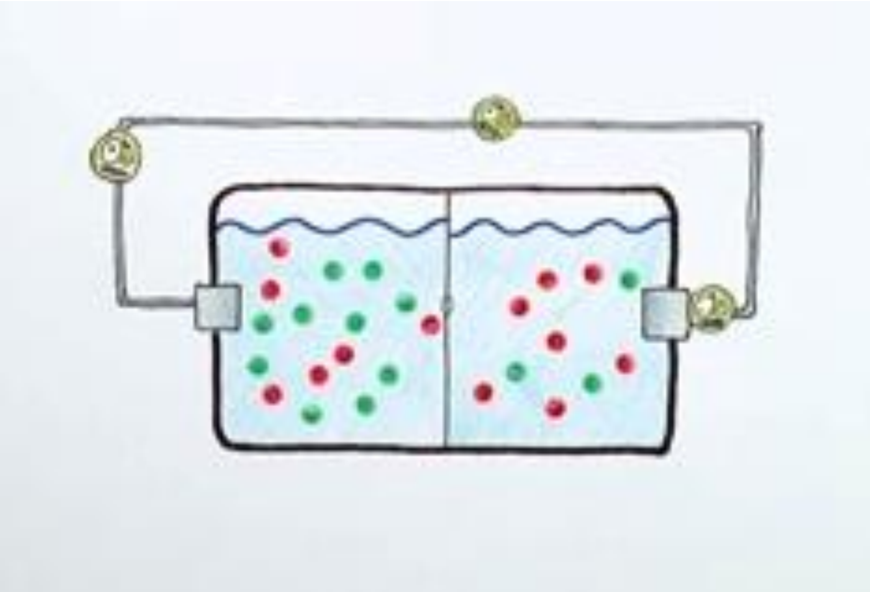


Figure 6: Osmotic power. Animation 1
Source: École polytechnique fédérale de Lausanne (EPFL)

If the system is used with seawater and fresh water, salt ions in the seawater pass through the membrane into the fresh water until both fluids have the same salt concentration. And since an ion is simply an atom with an electrical charge, the movement of the salt ions can be harnessed to generate electricity.

“EPFL's system consists of two liquid-filled compartments separated by a thin membrane made of molybdenum disulfide. The membrane has a tiny hole, or nano pore, through which seawater ions pass into the fresh water until the two fluids' salt concentrations are equal. As the ions pass through the nano pore, their electrons are transferred to an electrode - which is what is used to generate an electric current.

Thanks to its properties the membrane allows positively-charged ions to pass through, while pushing away most of the negatively-charged ones. That creates voltage between the two liquids as one builds up a positive charge and the other a negative charge. This voltage is what causes the current generated by the transfer of ions to flow."

The power of the system depends on a nano pore size, with systems with bigger diameter of the nano pore demonstrating higher electric current but lower voltage, and systems with smaller sizes of nano pore increasing voltage but lower current. Researchers are testing the system efficiency to get optimal osmotic power.

According to theoretical predictions the potential of the osmotic power is huge, a $1m^2$ membrane with 30% of its surface covered by nano pores should be able to produce 1MW of electricity - or enough to power 50,000 standard energy-saving light bulbs. Molybdenum disulfide (MoS2) is easily found in nature or can be grown by chemical vapor deposition and this system can be adapted to produce electricity in many river estuaries.

The theoretical potential of salinity gradients (osmotic power) derived from salinity differences between fresh and ocean water at river mouths is estimated at 1,650 TWh/yr (1 terawatt hour = 10^{12} watt hour).

Osmotic power - a promising source of truly blue energy, no pollution, no emissions, silent, no moving parts, direct production of electricity.

1. Answer the questions:

a) What are the possible renewable energy resources in the ocean?

b) What is the estimated power potential of the waves, tides and salinity gradient?

2. Potential energy from Bay of Fundy

Read the number of kilowatt hours from the electricity meter in your home.
Make a note of the reading time.
Repeat the next day's reading at the same time.

a) Calculate energy consumption for one day.

b) Calculate in kWh the potential energy $E_p = mgh$ of 200 billion tons of water in Bay of Fundy elevated/falling at/from 8.5 m (why 8.5 rather than 17?) 4 times a day (why 4 rather than 2 times?). Take $g=9.81\ m/s^2$.

c) Estimate for how many houses, like yours, the tidal energy from the Bay of Fundy would be enough. Pay attention to use the right units.

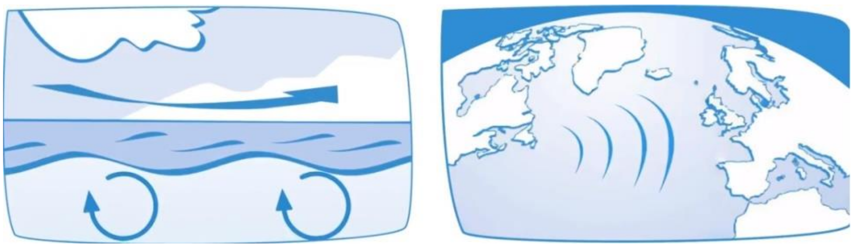
2 What causes waves?

It is generally known that if the surface of the water is disturbed, a wave will be created - a local water bulge that spontaneously spreads over long distances. In the case of a very large disturbance, for example a strong earthquake, a large wave can be created, called a tsunami, which can propagate to thousands of kilometers and the energy it carries can be massively destructive when reaching a shore (Phuket, Tailand 2004). The energy of these waves cannot be used to produce electricity because they occur sporadically and the amount of energy they carry is impossible to use technically. Only the waves that are caused by steady, moderate winds are a promising resource for power generation.

The cause of the wind is the Sun, which every day heating up the changing areas of the Earth, generating difference in atmospheric pressure, which is the cause of the wind.

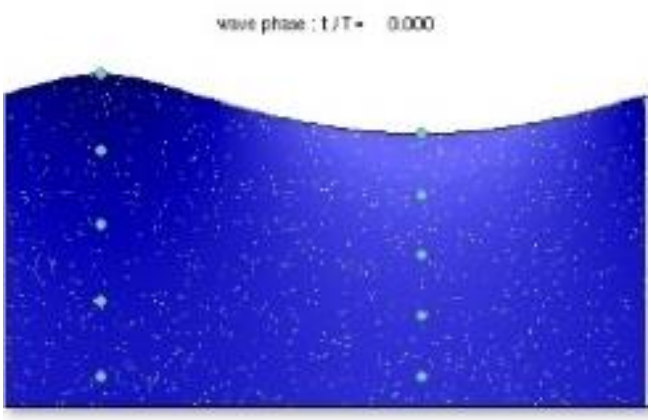
When the wind blows over the surface of the ocean, the momentum of air molecules is transmitted to the molecules of water. This causes the thin layers of water to flows one on top of other to form a swell. This deformation increases the impact of wind on the water and increases the height of the swell, until the wind force is no longer able to raise the water to a higher level. The wave is created and propagated in the direction of the wind (Animation 2).

Animation 2: Wave formation and propagation



The water does not move with the wave in the direction of the wave motion. It is rather a kind of circulation (Animation 2), with a slight displacement of the upper water layers, on a distance being some part of the wavelength in the one cycle. The wavelength is the distance between the two closest wave crests. As the depth of water increases, the circulation area decreases and the linear water displacement decreases too (Animation 3).

Animation 3: Water movement in a wave



In the region where wind is blowing across the ocean surface and waves are being generated, the sea surface is characterized by steep waves with many different lengths moving randomly in the direction of the wind. This condition is referred to as "sea". How large the waves get is dependent on 3 factors: the strength of the wind, the amount of time the wind blows and the distance (called fetch) over which the wind blows in a straight line across the ocean.

The amount of energy in a single wave is considerable. The potential energy of a set of waves is proportional to wave height squared times wave period (the time between wave crests). Longer period waves have relatively longer wavelengths and move faster.

The potential energy is equal to the kinetic energy (that can be expended). Wave power is expressed in kilowatts per meter at a location, such as a shoreline. Excluding waves created by major storms, the largest waves are about 15 meters high and have a period of about 15 seconds. Such waves carry about 1700 kilowatts of potential power across each meter of wave front. A good wave power location will have an average flux much less than this, maybe about 50 kW/m.

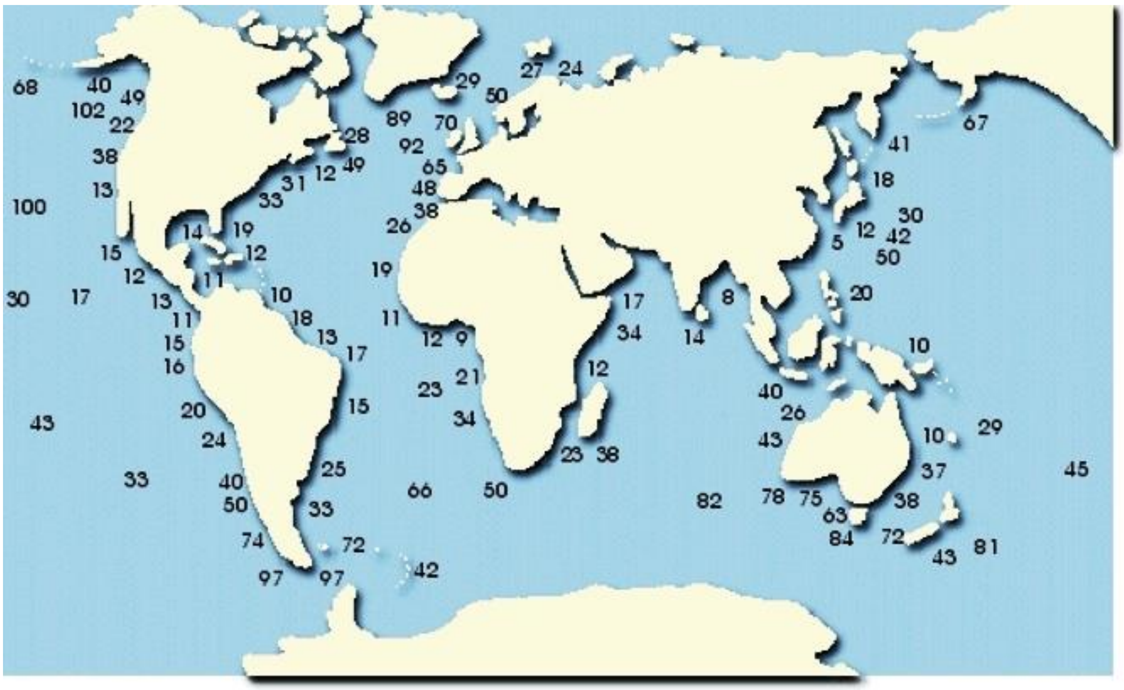


Figure 7 - The Global Wave Resource in kW per metre of crest. (Pelamis Wave Power)
Source: Murdoch University

For a typical wave of 10-second period, the power flux rate is 40 kW/m if the amplitude is 1m (gentle waves) and 1000 kW/m if the amplitude is 5 m (large waves). In the latter situation (high waves of a single frequency), the theoretical power available is 1000 MW per km of the coastline. This is comparable to an ordinary coal-fired power station. However in practice only a fraction of this energy can be extracted, because wave intensity has a large variability hourly, daily and seasonally (Wave resources, Murdoch University).

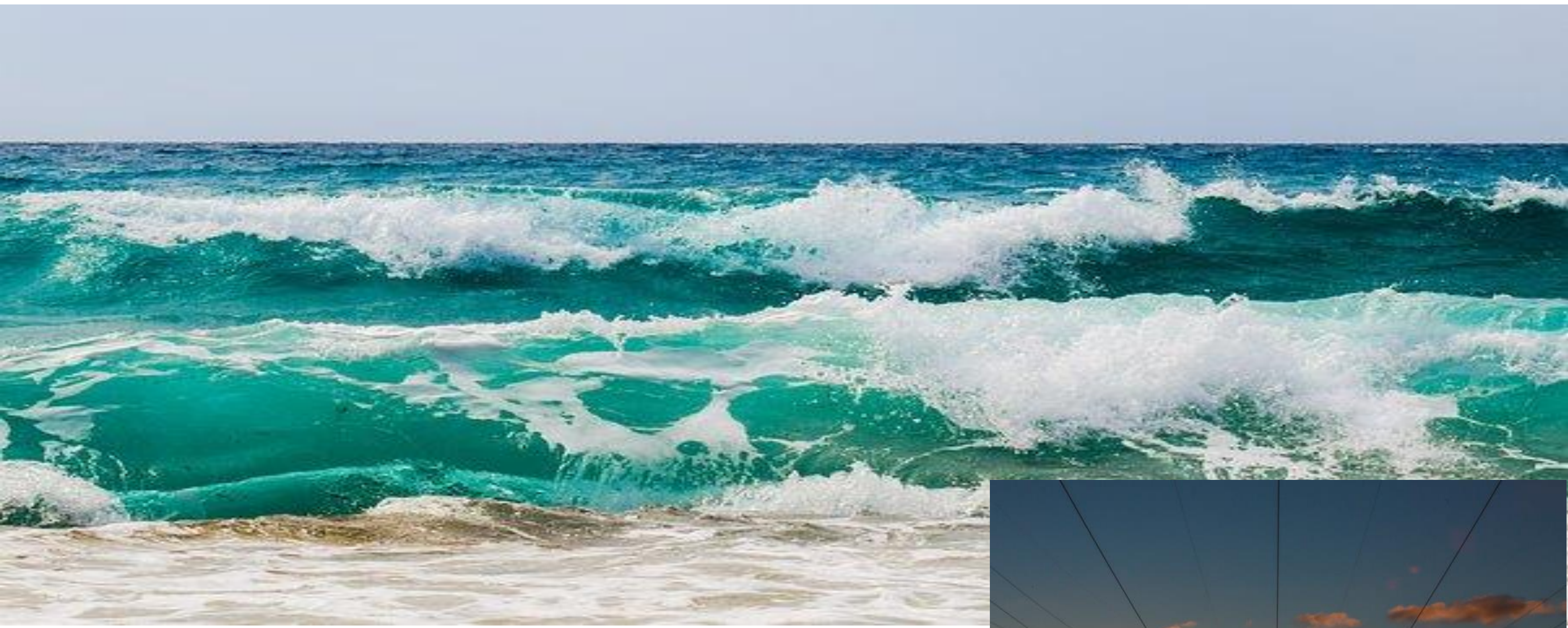
The World Energy Council has estimated the global wave power resource is in excess of 2 TW (1 terawatt = 10^{12} W), with potential for generation of more than 2000 TWh annually (World Energy Council, 2007).

Wave power has the potential to yield much more energy than tidal power. The energy potential of waves is vast, and wave power can be exploited in many locations. Countries with large coastlines and strong prevailing winds could produce five percent or more of their electricity from wave power.

3. Regions of the world with the greatest potential of energy from waves:

Using Figure 7, indicate three regions of the world with the highest energy potential from waves.

3. How to draw energy from the waves?



There are many devices based on different technologies, made on different scales that convert wave energy into electricity. There are even more concepts in the phase of more or less advanced designs or prototypes, tested in laboratories around the world.

There are machines made in full scale, currently working and supplying power to the power grid on land. There are even more prototype devices made on a smaller scale, tested in laboratories or wave channels. The question is whether these machines, not subsided, will produce enough energy to pay back the cost.

However, the advancement of some solutions suggests that the commercial production of machines that uses wave energy to produce electricity will be possible soon.

According to the Report IPCC 2012 the acquisition of energy from waves is basically based on three concepts:

- Oscillating Water Column (OWC)
- Oscillating Body (OB)
- Overtopping

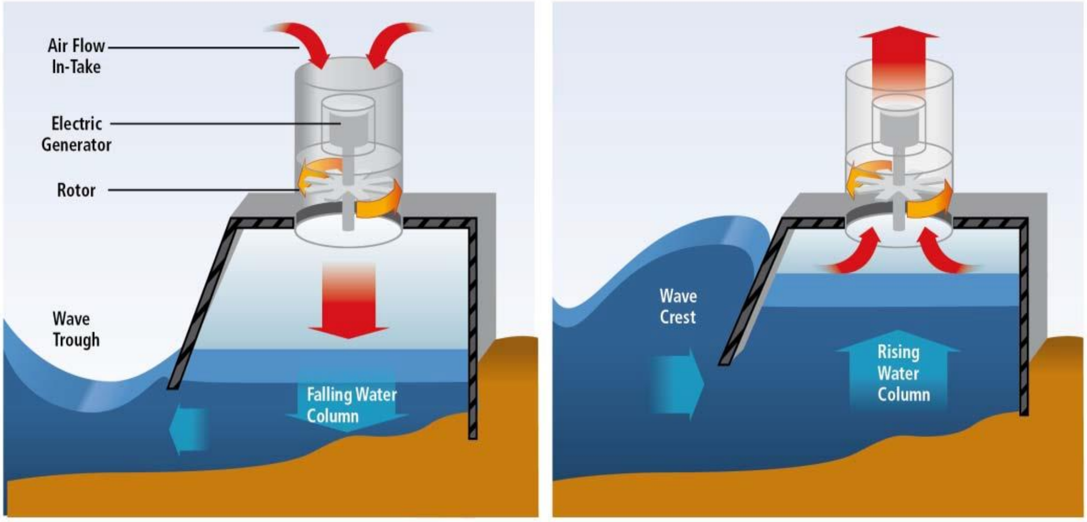


Figure 8 - Oscillating Water Column Source: Report IPCC 2012.

In an OWC system, a stream of ejected or sucked air from/into the chamber above the water column drives the turbine. There are solutions that, using the same principle, pump water. Water has 832 times higher density than air, which allows the reduction of the size of the turbine while maintaining a similar energy transfer.

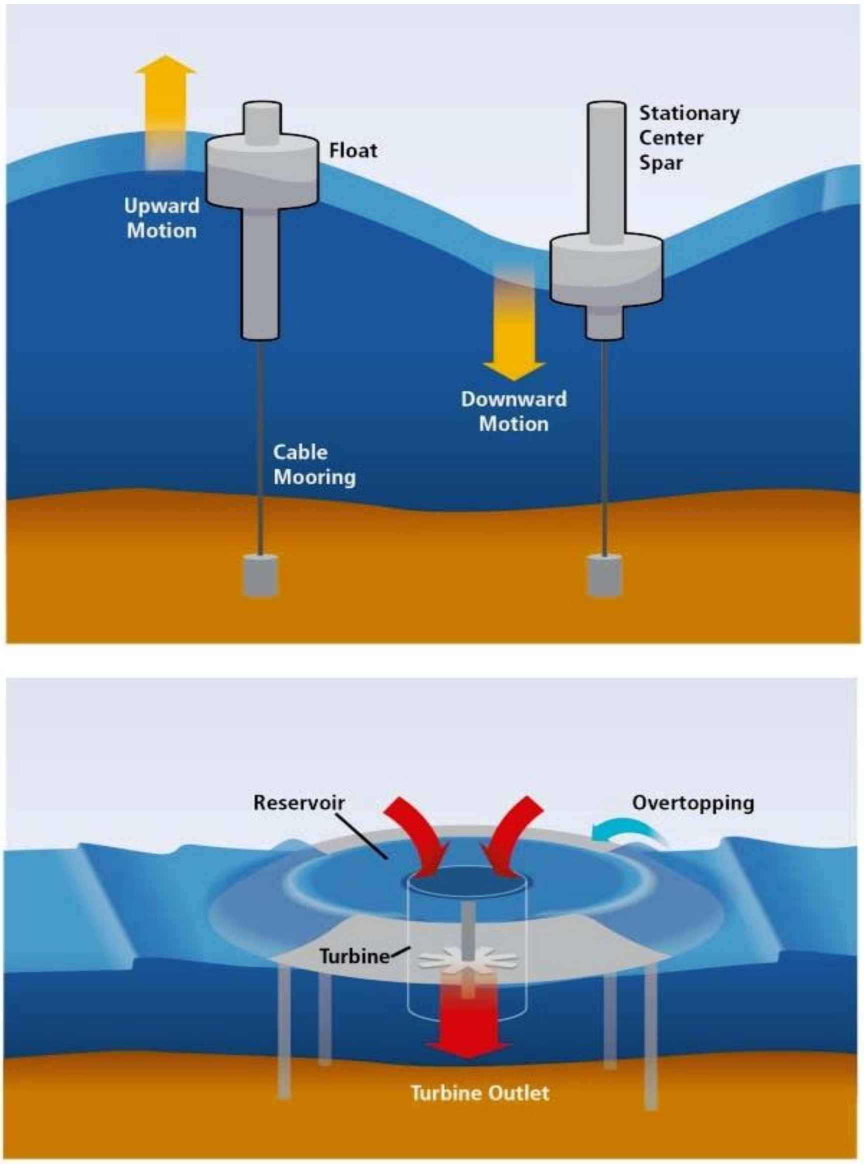


Figure 9: Oscillating Body and Overtopping concepts. Source: Report IPCC 2012

The Principle of the OB system is simple. The mechanical drive line contains a linear transmission for conversion of linear to rotating motion, driving a turbine. The work of buoyancy force of the floater on the road equal to the wave height can generate quite a lot of electricity.

The overtopping system is based on the principle used in hydropower plants. The water from the upper reservoir flows down, driving the turbine. Incoming waves fill in the reservoir with water.

Further ahead some examples of wave energy converters are presented, for which tests in the sea or lab confirmed their suitability for use as a source of clean energy.

4. Energy (OWC) from waves in bathtub.

Material:

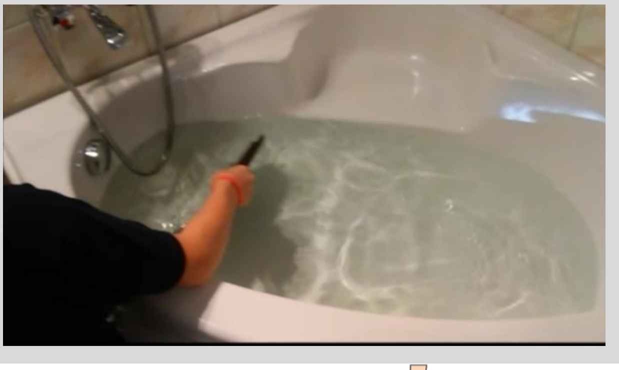
- Plastic tray to generate waves;

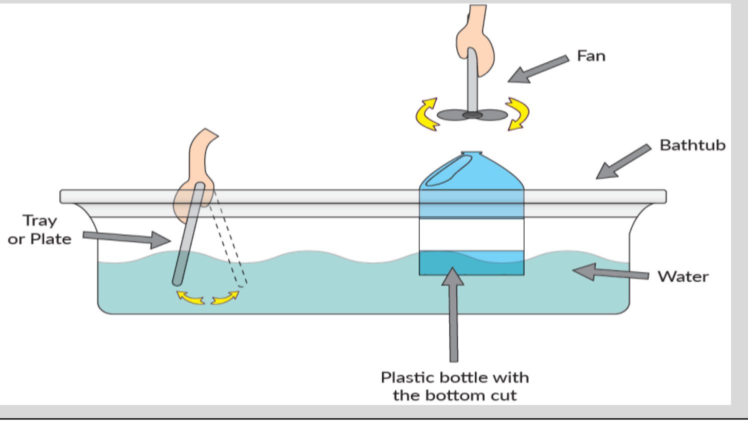
- Plastic bottle with a large diameter (~ 18 cm) with cut-out bottom;

- A thin board with a cut-out hole for the bottle neck;

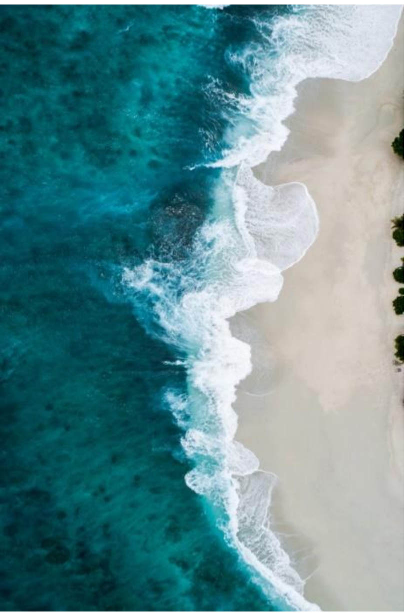
- A fan made of a square piece of thin paper, cut along diagonals and bended corners as shown.

The fan is fasten with a pin to a piece of wooden slat. The waves are generated in a bathtub filled halfway with water. Do the experiment by following the video below and image.





Energy from waves in a bathtub.



5. Estimate the power in OB system

What power can be obtained from a floater with a volume of 1m^3 moved by a wave of 1 meter high and a period of 10 seconds? (Neglect the floater's weight)

Compare the result with the power needed in a typical family house (1.5 kW).

Note: The body, immersed in water, has a buoyancy force upward, equal to the weight of water with a volume equal to the volume of this body.
Pay attention to the use of the right units.

Energy from floaters

An empty floater with a volume of e.g. 1 m^3 immersed in seawater will press up with a force of approximately 10,000 N. Knowing the shift of floater and the time in which it occurred, we can estimate the power that can be obtained. This force is additionally multiplied by a lever, which is about 3 times longer than the working arm of the hydraulic attenuator (Figure 10, section B). The attenuator acts like a pump, supplying the fluid under high pressure.

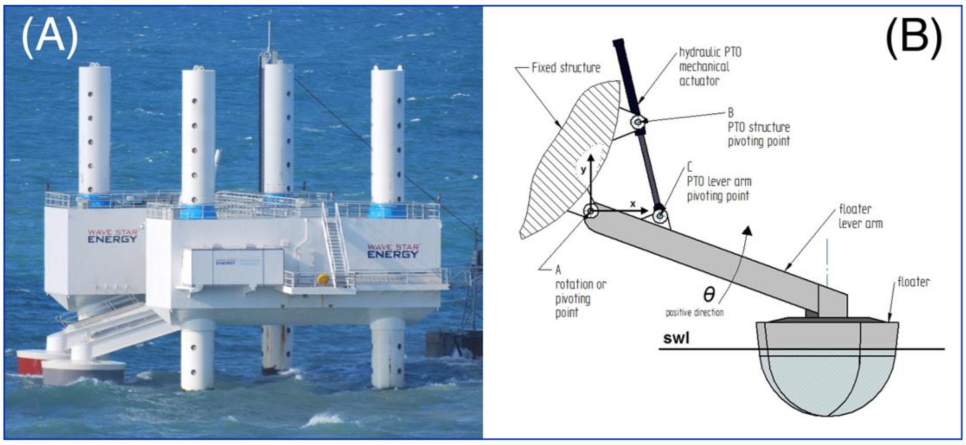


Figure 10: Wave Star machine in ½ scale (A) and the principle of work (B). Source: Wavestar

The operation is based on continuous movement of the floaters through the waves, thanks to which it is possible to press the fluid under high pressure. The fluid, under sufficient pressure, drives the hydraulic motor, which is connected to the generator producing electricity.

The machine should adapt to marine conditions and the most effective energy costs. Scalability of the machine (floaters with a diameter of 5m to 10m) makes it very easy to adapt to marine conditions.

A WaveStar machine is based only on standard components, standard technology of wind and coastal turbines. The machine is placed on a pile construction on the seabed - for 7 to 30 meters of water. For safety reasons, it should be turned off if the waves exceed 8 meters - storm protection mode. In this case, the entire structure moves upwards over the wave level.

The model from Figure 11 generates a power of 600 kW, is connected to the grid and supplies 400 houses. A 6 MW machine is planned.

Figure 11 - Commercial Wavestar 600 kW (2010). Source: Wavestar

Figure 12 - Wavestar machines in synergy with wind turbines.
Source: Wavestar

Wave snake converter

The wave snake converter is a technology that uses the motion of ocean surface waves to create electricity. The machine is made up of connected sections which flex and bend as waves pass, as is shown on Figure 13. This snake-like motion is used to generate electricity.

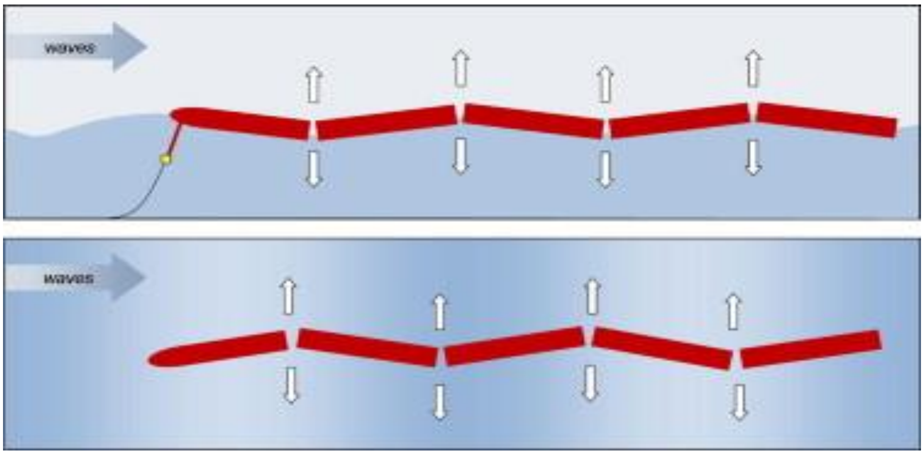


Figure 13 - Vertical and horizontal movement of the sea snake sections.

The machine is an offshore wave energy converter, operating in water depths greater than 50 m. The machine consists of a series of semi-submerged cylindrical sections linked by hinged joints. As the waves pass along the length of the machine, the sections move relative to one another. The wave-induced motion of the sections is resisted by hydraulic attenuators which pump high pressure oil through hydraulic motors via smoothing hydraulic accumulators, as is shown on Figure 14.

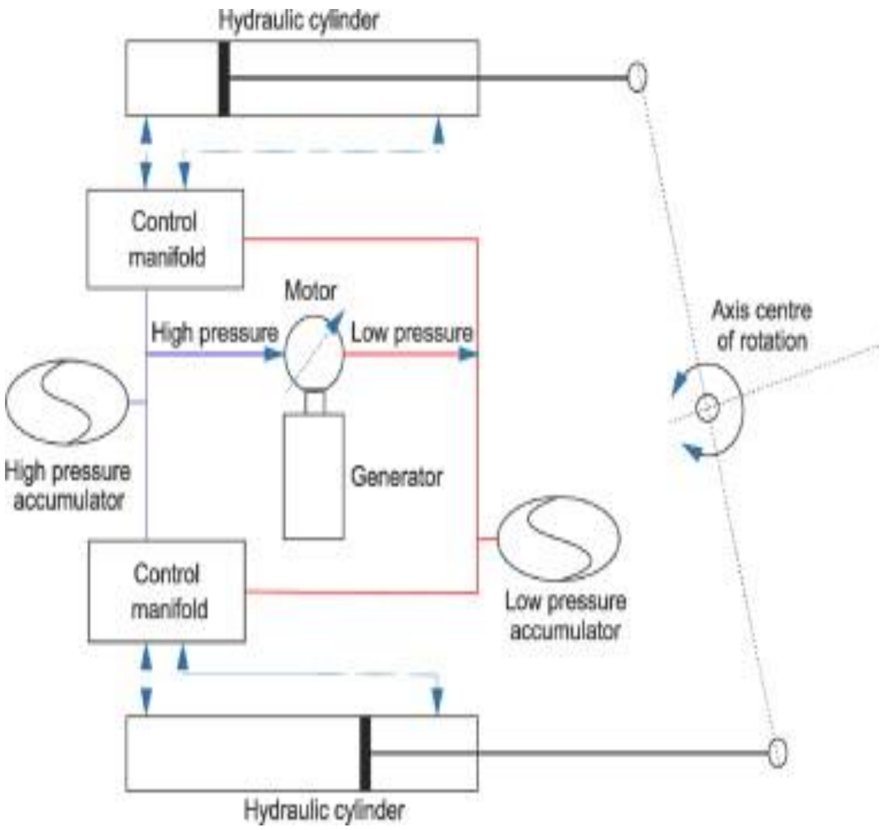


Figure 14 – Simplified schematic system of wave snake converter.

The hydraulic motors drive electrical generators to produce electricity. Electricity from all the joints is fed down a single umbilical cable to a junction on the sea bed. Several devices can be connected and linked to shore through a single seabed cable.

The device is an attenuating wave energy converter. The machine responds to the curvature of the waves (their shape) rather than the wave height. As waves can only reach a certain curvature before naturally breaking, this limits the range of motion through which the machine must move but maintains large motion at the joints in small waves.

Large models (180 m long) can supply electricity with a capacity of 750 kW.

Figure 15 - A section of Pelamis 180 m model. Source: Pelamis Wave Power.

Figure 16 - Pelamis P2-001 technology failed. Source: Scotrenewables

However, this interesting technology has, not yet, been successful.

The HiWave – A Resonant Wave Energy Converter

Wave energy converters presented above, have large weight and are expensive, which prevented commercial harvesting of the wave power.

The HiWave project comes with a new solution to the wave power generation, with a compact, high-efficiency wave energy converter.

Figure 17 - HiWave and its key properties

The HiWave device includes three key inventions within drive line and control technology.

Firstly, a module with pneumatic pretension is used to allow the attachment of a lightweight system with a high natural frequency of oscillation.

Secondly, it is used a method called Phase Control Technology to get the buoys oscillate in resonance with the incoming waves.

This strongly amplifies the motion and allows a large amount of energy to be absorbed by the small buoy, and this amplified linear motion is then converted into clean electricity using a new type of mechanical drive line located inside the buoy.

The mechanical drive line contains a cascade gearbox which has a unique design for high reliability and effective conversion of linear to rotating motion.

.

Figure 18 - A cascade gearbox of HiWave

It is like on a swing. If we skillfully add energy at the right moment then the energy of the swing increases (positive feedback) and we lean out more and more. As we push the swing at any moment, its energy does not grow.

These small buoys have low inertia, which means that they are well optimized for the amplified motion obtained in the phase control, and also have a better survival rate even in storm conditions.

This technology offers economic savings in operation and maintenance costs.

Compared to current wave power technology, HiWave converters with buoys can deliver more energy per tonne of device.

The wave energy converters have been also designed to work in large wave farms, where dozens of units can be combined to enable mass production at a lower cost.

Extensive testing has proven that the unique control method works reliably.

Prototypes have, also, been tested in the most severe storm conditions that often occur on the Atlantic coast, proving good survivability.

This technology offers a power density (kW/ton device) that is more than five times higher than existing solutions and an effective service scheme expected to result in a leveled cost of energy below 0.15 EUR/kWh in volume (InnoEnergy 2017).

Wave energy direct conversion into electricity

The EPoSiL project coordinated by BOSCH is aimed at investigating the possibility of obtaining electric energy from waves using a material that is characterized by perfect insulation and elasticity, playing a role of converter.

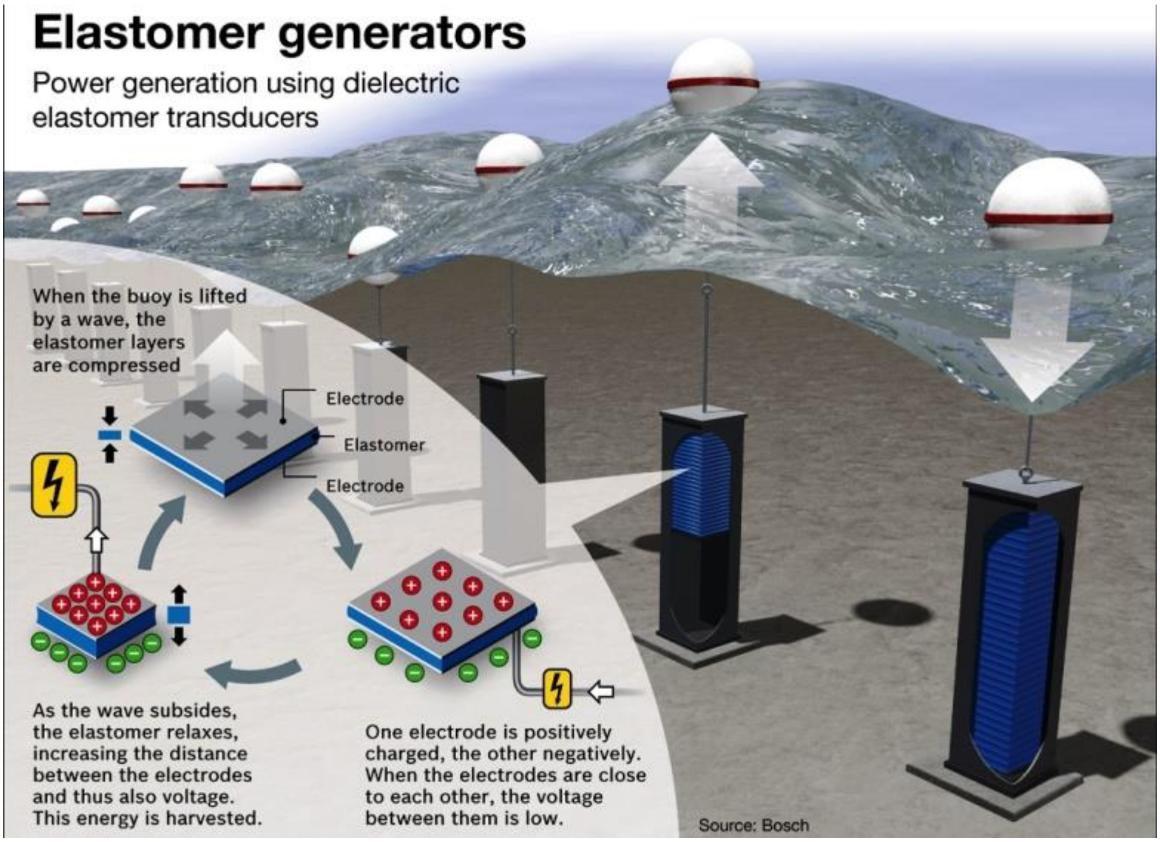
The idea of the project is based on a simple relationship between the electric charge *Q* accumulated on the electrodes of a flat capacitor and the voltage *U* between them

$$Q = c \cdot U$$

where *c* is the capacity of the capacitor, proportional to the surface area *s* of the electrodes and inversely proportional to the distance *d* between the electrodes.

$$c \sim \frac{s}{d}$$

Figure 19 – Power generation using dielectric elastomer transducer. Source: Bosch



The energy converter consists essentially of a three-layer film. At the top and bottom there is a conductive layer (electrode). The middle layer is a very flexible elastomer with excellent insulating properties, which can also be produced under industrial conditions. The wave motion transfers mechanical force to the converter. The wave first squeezes the elastomer, which brings the two electrodes close together. An electrical voltage is applied from the outside: one of the electrodes is charged positively, the other is negatively charged. With further wave motion, the force transmitted to the converter decreases. The elstomer expands and becomes thicker again. This causes that the distance *d* rise up. The charge *Q* remains unchanged, while the distance between the electrodes increases, i.e. *c* decreases, so *U* must increase. This effect causes an increase in the electric energy in the converter. Electric energy of a charged capacitor is equal:

$$E_c = \frac{Q \cdot U}{2}$$

so, if *d* increases *U* and E_c increases too.

The desired effect is that the mechanical energy of the wave is converted into electrical energy, which is passed on, and the cycle can start again. Wave energy is converted to electricity directly, without using a turbine.

In practical use, not one but many layers are used, the electric current from individual layers is added up. There are many technical possibilities that allow ocean waves to squeeze silicone layers. The laboratory model of the device was created by TU Darmstadt. Work has been undertaken to prepare the waveform generator model on a smaller scale, for trials in the wave channel. The target efficiency of converting mechanical energy into electricity is about 50%.

6. Acquiring energy from waves

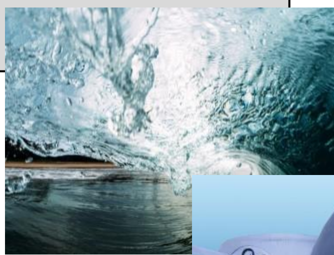
Answer the questions:

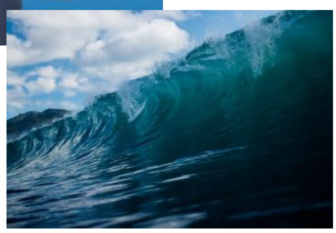
a) What are the technologies for obtaining energy from waves?

b) Which technology gives the most energy per unit of weight of the device?

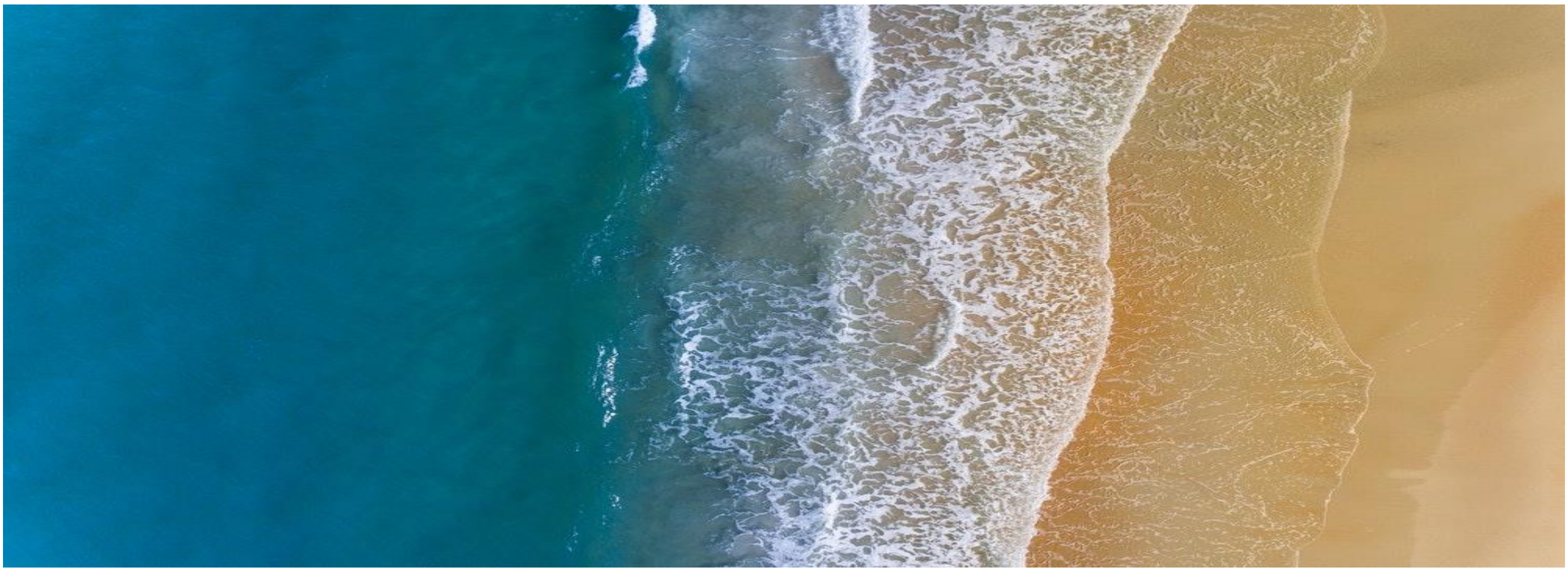
c) Is it possible to obtain energy from waves without using turbines?

d) What is the global potential energy of waves?





4. Where are the tides coming from?



Before we answer the question: what is the origin of tides? think about how the Earth and the Moon move. We will not take into account the influence of the Sun or other celestial bodies. Let's assume that the Earth is a sphere completely covered with a layer of water. For simplicity assume, that it does not rotate around its own axis. In fact, the Earth revolves around its axis once a day. This causes it to be somewhat flattened, but this has no effect on the tides. According to Kepler's laws, the Earth and the Moon will move with an orbital motion at a constant angular velocity around the center of the mass (also called the barycenter). Suppose also that the orbits of the Earth and the Moon are circular. The center of the Earth will move around the barycenter, in a circle with a radius *d* equal to the barycenter distance from the center of the Earth.

$$d = r\frac{M_M}{M_M + M_E}$$

where

r=384,400 km, distance between center of the Earth and center of Moon
M_E=5.972E+24 kg, mass of the Earth
M_M=7.3477E+22 kg, mass of the Moon

For the stability of the Earth-Moon system, the centrifugal acceleration of Earth center in this motion must be, in value, equal to the centripetal acceleration generated by gravitation of the Moon.

$$G\frac{M_M}{r^2}$$

where

G=6.674E-11 $m^3/kg\ s^2$, gravity constant

To determine the tidal acceleration of any point on the surface of the earth, we must first answer the question:

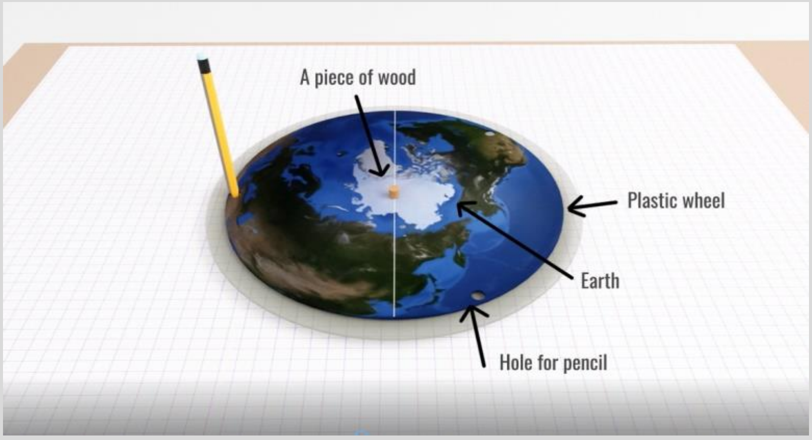
How does any point on the surface of Earth move in the orbiting Earth-Moon system?

The answer we can get performing the following simple experiment 3 described below. As a result of the experiment, we will receive three circles with the same radius, equal to the radius of the circle drawing by the center of the Earth.

7. How the points on the Earth surface moves on?

Material:
- Board or a thick cardboard with the size of A4 paper;
- Sheet of checkered paper;
- 2 pins;
- Plastic arm with two small holes in distance of 25 mm;
- Plastic wheel (e.g. cut from a box of fruits) with diameter of 80 mm;
- A pencil

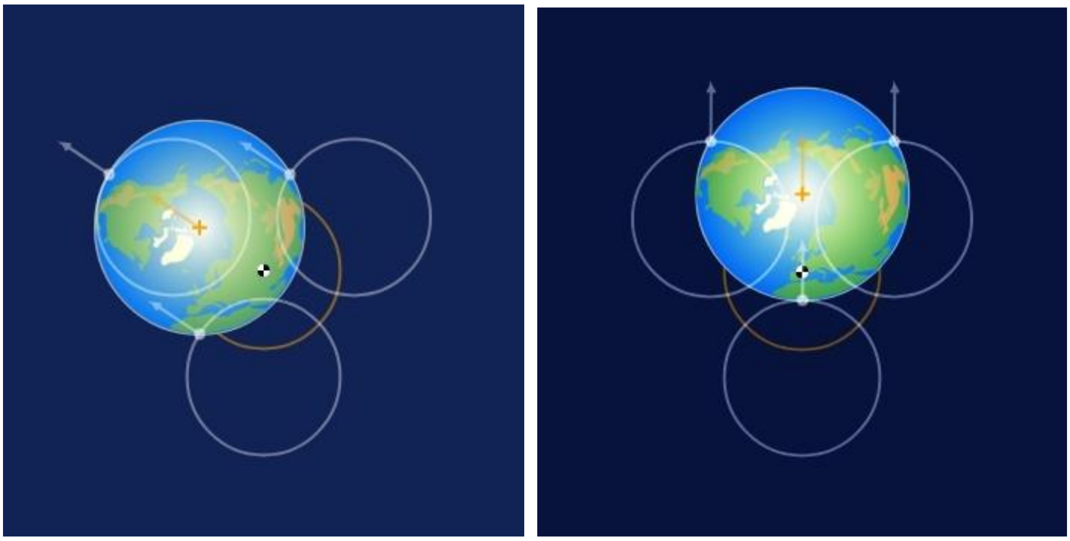
On a plastic wheel, draw a circle of Earth (70 mm in diameter) and a meridian using color markers, make 4 holes in it, small one in the circle center for a pin, and 3 holes on the circle for a pencil. We will use them to plot the points of motion path. Fold it all together as in the animated picture below.
Then make one turn of the plastic wheel, keeping the meridian remain parallel to the edge of the page. For simplicity, we neglect the rotation of the Earth around its axis and the inclination of the Earth's axis. Pencil inserted into one of the holes will draw the path of moving point. Repeat the movement for the remaining holes.



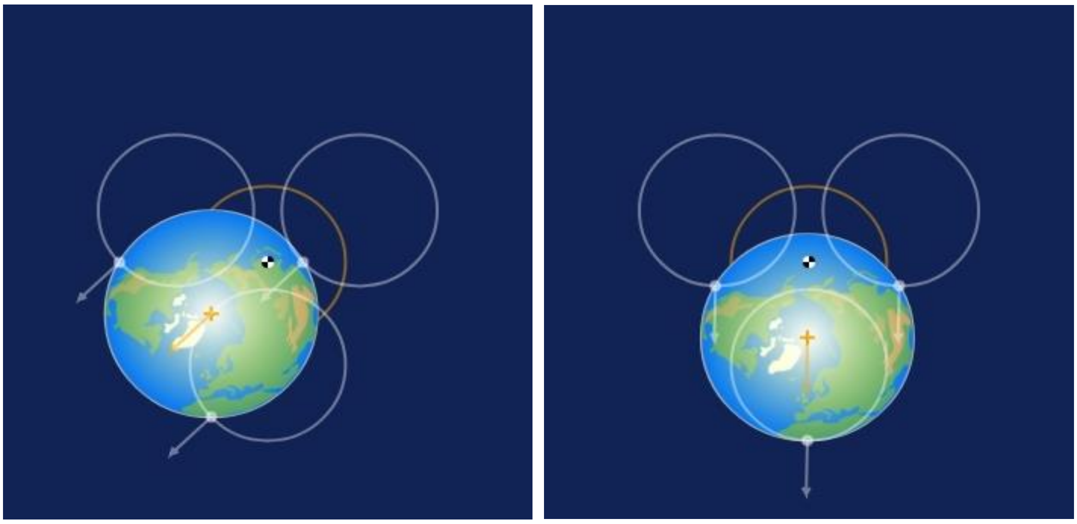
Instructions on how to assemble the elements and perform the experiment.

Analyze what we have received and what important conclusions we can formulate.

For better understanding the pictures below show the 4 phases of the orbital motion of the Earth. From the pictures it appears that the center of the Earth and 3 points lying on Earth's surface moves in circles with the same radius *d*. Hence the conclusion that the acceleration of the center of the Earth and in the points lying on its surface is the same as for the value. The direction of the acceleration relative to the Earth changes, but always is outward of the circle and opposed to Moon direction



b) a)



c) d)

Figure 20 - The trajectories and accelerations of chosen points on the Earth's surface in 4 phases of orbital motion of Earth and Moon system.
Source: beltoforion.de

Since they perform the same motion, the accelerations associated with it will be the same, as in the value and direction as well. This is shown in Figure 21, on the upper part. Moon is on the right, not visible, out of scale.

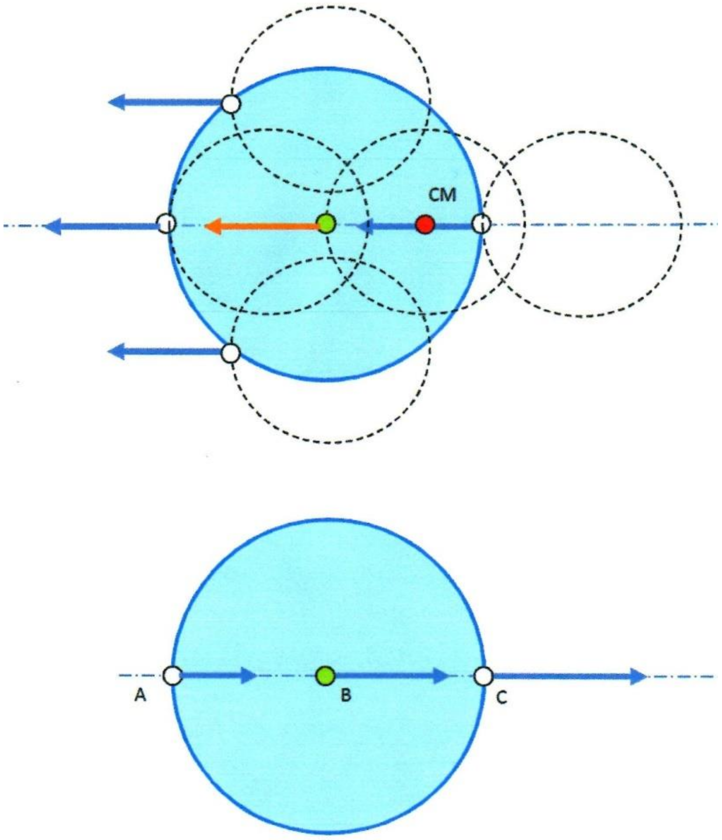


Figure 21 – Accelerations in some point on orbiting Earth

To determine the value of tidal acceleration, we must also take into account the acceleration caused by gravitational pull of the Moon, which is different at different points of the Earth. As we can see on lower part of Figure 21, this acceleration is greater on the side of Earth facing the Moon and is smaller on opposite side. The calculations of tidal acceleration are complex, but when points A and C, are on one line with centers of Earth and Moon it can be calculated simply.

For tidal acceleration in point A we can write

$$G\frac{M_M}{(R+r)^2} - G\frac{M_M}{r^2} = -1.07 \cdot 10^{-6}\ \frac{m}{s^2}$$

where
R=6378 km, radius of the Earth

And for point *C*

$$G\frac{M_M}{(r-R)^2} - G\frac{M_M}{r^2} = 1.13 \cdot 10^{-6}\ \frac{m}{s^2}$$

Doing the calculations for all the points of the Earth's surface, we are getting the well-known tidal force field. In points A and C and in their surroundings, the water must rise, a level difference must arise which will be a source of centripetal force, balancing the tidal acceleration.

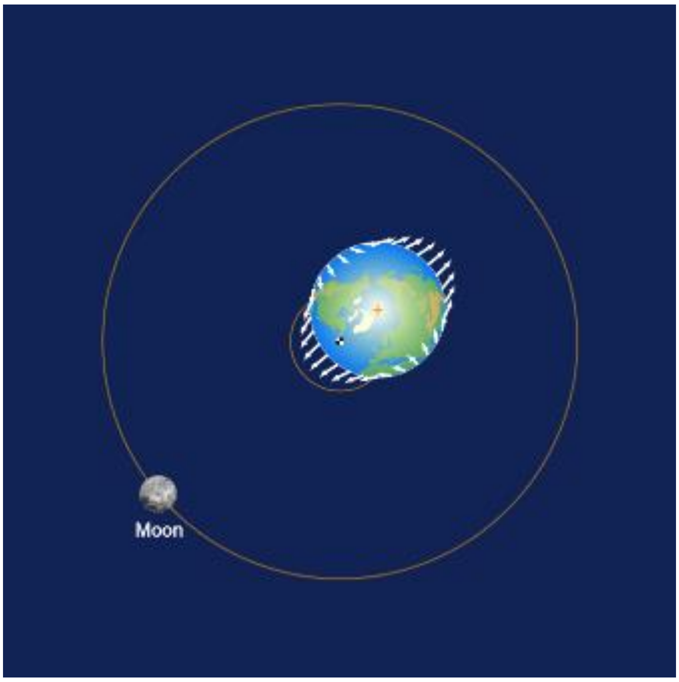
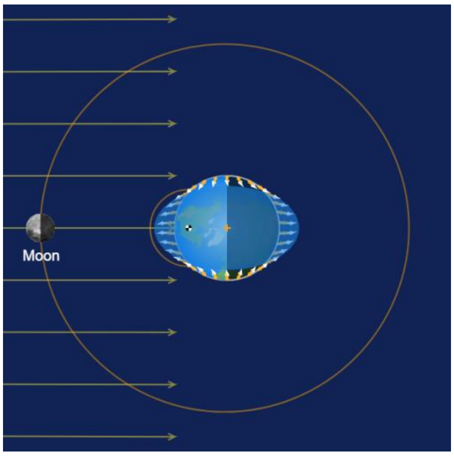


Figure 22 - Tidal force field (white arrows)
Source: Beltooforion.de

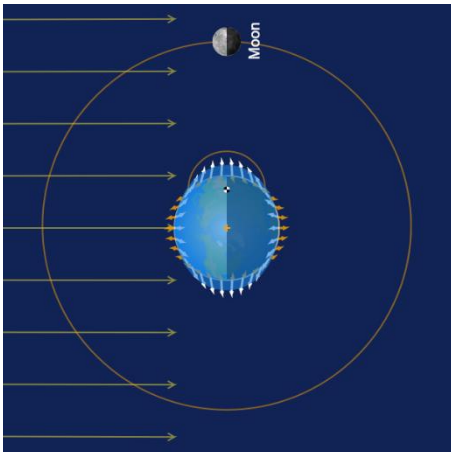
We have then demonstrated the existence of two tidal bulges, in opposite directions and slightly different intensity, being stronger the one towards the Moon. It's all we need to explain tides: the tidal effect is only due to the gravity gradient.

As we can see in Fig. 22, in some points of the Earth's surface, the tidal forces are tangent to a sphere; that implies a force displacing the water towards the sublunar or anti-lunar points, where it collects.

The same tidal effect we have for the Sun. the tidal forces acting on the Earth’s surface are a combination of the tidal effects of the Moon and the tidal effect of the Sun. The computation of the latter one is done exactly like we did for the moon. Due to the greater distance of the Earth from the Sun the effects caused by it are a slightly smaller despite its significantly larger mass. Fig. 23 shows the two separate tidal bulges of the Moon and the Sun.



a)



b)

Figure 23: The tidal acceleration caused by the Moon (white arrows) and the Sun (orange arrows at different positions of the Moon). The blue ellipse is the shape of the resulting tidal bulge obtained by adding both acceleration vectors. The light beams and shadows give a hint at the position of the Sun. Source: beltoforion.de

8. Two tides each day

Read article titled Tides explained published by Ingo Berg on webpage http://beltoforion.de/article.php?a=tides_explained&hl=en&da=1&s=idPageTop#idPageTop

Watch animation of orbital movement of Earth and Moon around barycenter. http://beltoforion.de/article.php?a=tides_explained&hl=en&da=1&p=tides_applet

Answers the questions:

a) Is the barycenter always the same place inside the Earth?

b) What acceleration have any point on the surface of the Earth due to orbiting Earth – Moon system? Justify the answer.

c) Why we have two tides each day? Extensively explain the answer.

Resulting tidal bulge depends on the position of the Moon. When the line Sun-Earth line up perpendiculary to line Earth- Moon we have the Neap Tides. It happens at half Moon. Under these circumstances the gravitational bulges of the Moon and the Sun overlap destructively because the tidal forces of the Sun are acting against the tidal forces of the Moon. At neap tide difference between high tide and low tide are the smalest.

The opposed situation we have when Sun, Earth and Moon line up. Such an arrangement happens at every full Moon and new Moon phase. In this case the gravitational forces of Sun and Moon are forming a large tidal bulge. They are called the Spring Tides. At spring tide the difference between high tide and low tide are at their maximum.

The observable rise and fall of the sea level is influenced strongly by shoreline topography, ocean currents and the continents distribution on Earth. As a result different tidal cycles can be experienced in different regions of the world. They are described as semi-diurnal, diurnal or mixed tidal cycles.

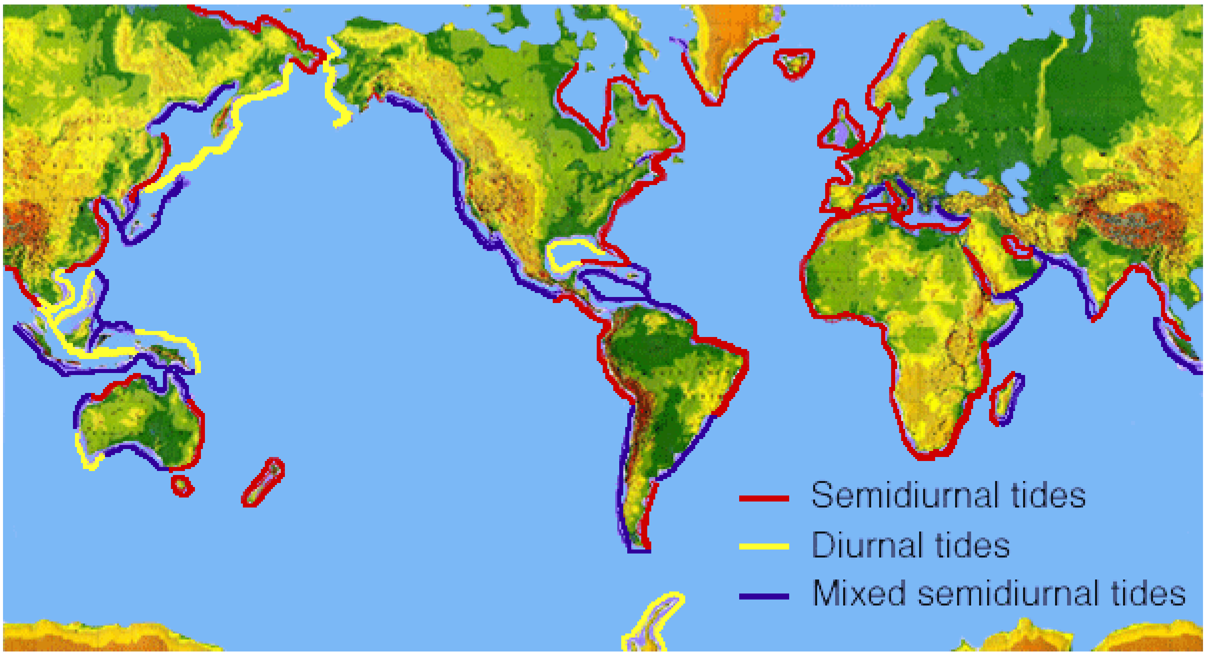


Figure 24 - Distribution of tidal cycles on earth.
Source: NOAA

A semidiurnal tidal cycle is a cycle with two nearly equal high tides and low tides every lunar day (a lunar day lasts about 24 hours and 50 minutes).This type of tidal cycle we could expect from a planet covered entirely with water and without any continents obstructing the free motion of water. As we can see in Figure 24 most places at the oceans on the Earth experience a semidiurnal tidal cycle.

A diurnal tidal cycle is a cycle with only one high and low tides each lunar day. Diurnal tidal cycles can be found in such a places as the Gulf of Mexico and on the East coast of the Kamchatka Peninsula.

A mixed tidal cycle is a cycle with two high and low tides with different sizes each lunar day. The difference in height between successive high (or low) tides is called the diurnal inequality. Areas with a mixed tidal cycle can be found alongside the West cost of the USA, in parts of Australia and in South East Asia.

9. Tidal cycles

Read the paragraph Tidal cycles in article titled Tides explained published by Ingo Berg on webpage http://beltoforion.de/article.php?a=tides_explained&hl=en&da=1&s=idPageTop#idPageTop

- Perform tidal calculations caused by the gravity of Sun. Search for the necessary data in the internet. (You can assume that the orbit is circular and the distance between the center of the Earth and the center of the Sun is 150 million km.)

Compare the results obtained with the values obtained for the tides caused by the Moon's gravity

- Answer the following questions:

a) What are the tidal cycles and what is their cause?

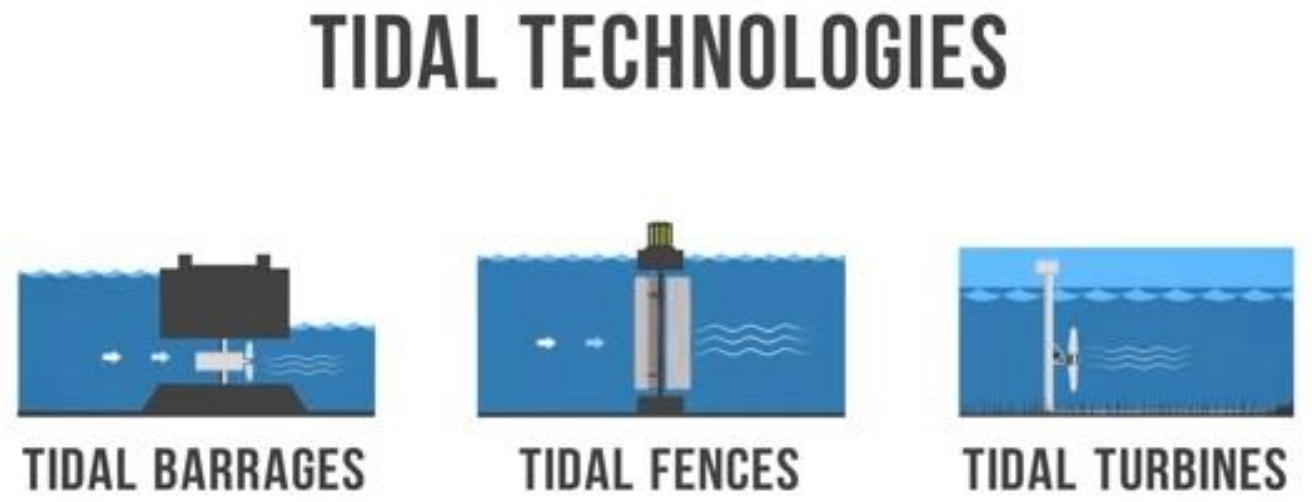
b) Why is the lunar day longer by about 50 minutes, than a day on the Earth?

c) Are there places on Earth with only one high and low tide each lunar day?

d) What is Neap Tide and Spring Tide and when do they happen?

5. How to harness tides to generate electricity?

We distinguish 3 technologies for the conversion of tidal energy into electricity: tidal barrages or tidal lagoons, tidal fences and tidal turbines. Only the first of them has been used on an industrial scale, since 1966.



Tidal barrages

The ideal location for conventional tidal power plant is a narrow, long bay or funnel-shaped in the form of estuary, with high tides. Such conditions meet the mouth of the La Rance River to the English Channel, France. On the river a dam of 330 m long was build. The plant generates energy by allowing water to flow into or out of the estuary through the turbines. The capacity of installed hydro turbines reaches 240 MW.

Figure 25 – Dam and tidal powerplant on La Rance, France

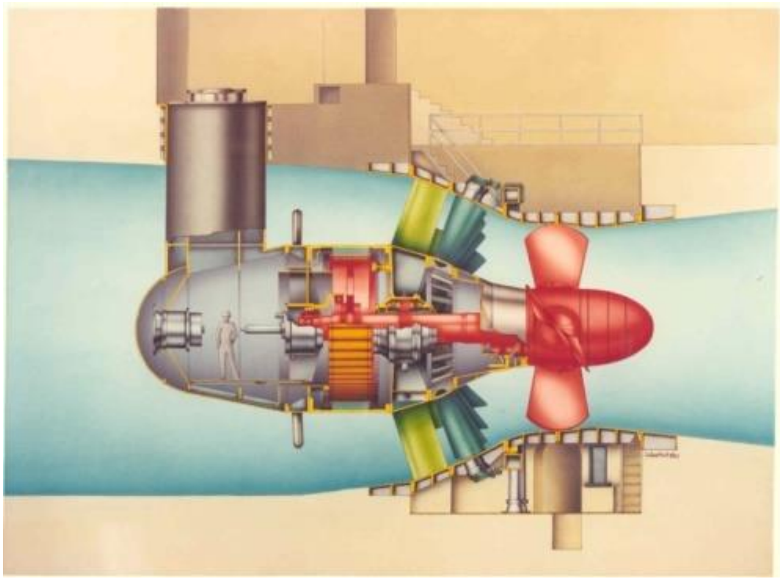


Figure 26 – Bidirectional turbine (La Rance)

A special, movable dam has been installed, equipped with six valves enabling faster emptying / filling of the basin. The river basin has an area of 22 square kilometers and can hold 189 million cubic meters of water. The tide at the mouth of the La Rance reaches 13.5 m. The power plant has 24 turbines of 10 MW each, which can work in both directions: at high tide and low tide. The tidal power plant on the La Rance River annually produces 550 GWh, securing electricity demand for 250,000 households.

Tidal lagoons

Bunded tidal barrages operate in a similar way to conventional tidal barrages but do not fully obstruct an estuary.

Single or multiple basin offshore tidal lagoons would be built on tidal flat in areas with high tidal ranges.

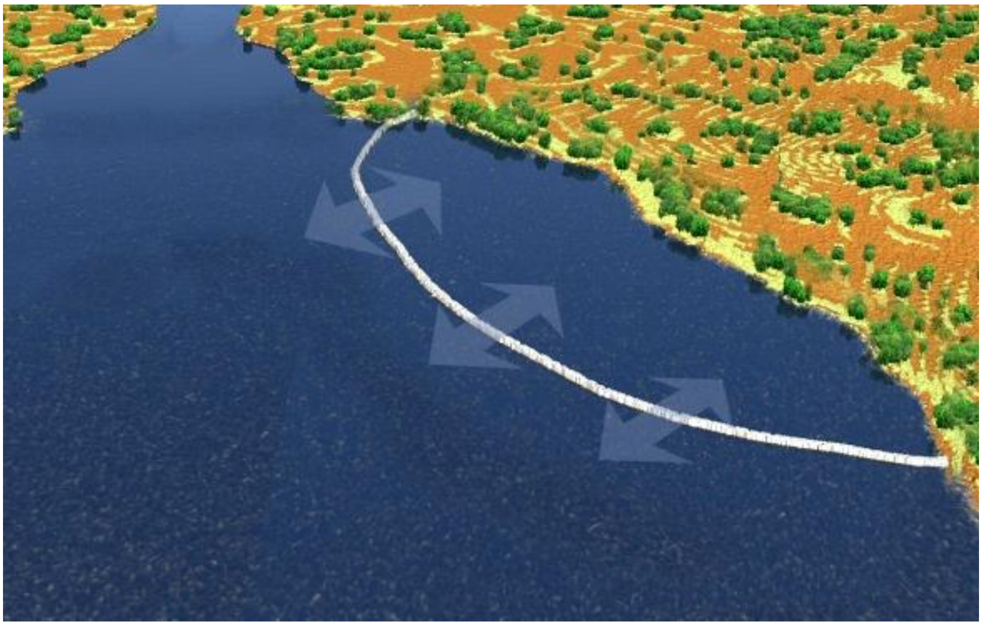


Figure 27 - Tidal lagoon with arrows showing direction of water flow with tides. Source Aquaret.

Jetstream Tidal lagoons

Conventional tidal lagoon technologies draw energy from the tidal range using turbines, with power generation windows, limited to incoming and outgoing tides.

The Jetstream project goes further: The Jetstream concept increases water transfer to and from the lagoon on both incoming and outgoing tides, resulting in higher differential generating heads and thus sustained power generating windows.

This water transfer is carried out by a variation of proven Venturo zero-energy pump technology.

A Venturo pump does not need external supply, operating thanks to flowing water and its inertia only.

Figure 28 - Jetstream Tidal Lagoon. Source: Water Powered Technologies.

A large number of Venturos are attached to the periphery of the lagoon's outer wall, which is a smooth, aerofoil shape. The pumps are operated by the increase in the water flow around the aerofoil shape which can be up to 25%.

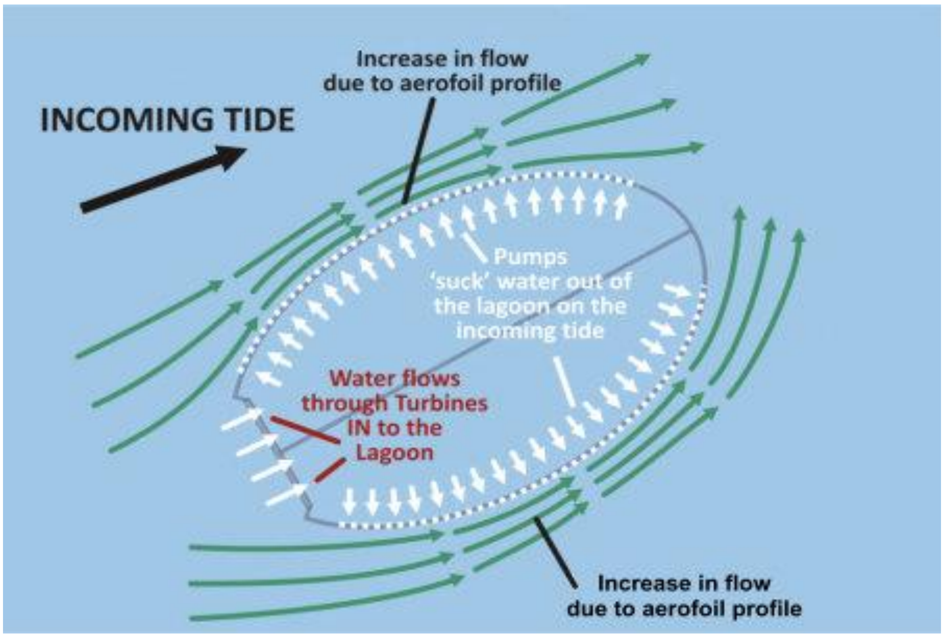


Figure 29 - Operation on incoming tide. Source: Water Powered Technologies

On the incoming tide, the Venturo pumps operate to pump water from the lagoon and on the outgoing tide they pump water into the lagoon. Tidal water is prevented from flowing into and out of the lagoon by the bi-directional turbines' wicket gates. The turbine gates are opened at around high and low tides and closed at times in between. This ensures that the turbines start generating power at the maximum height differential which optimizes efficiency and the power generation windows.

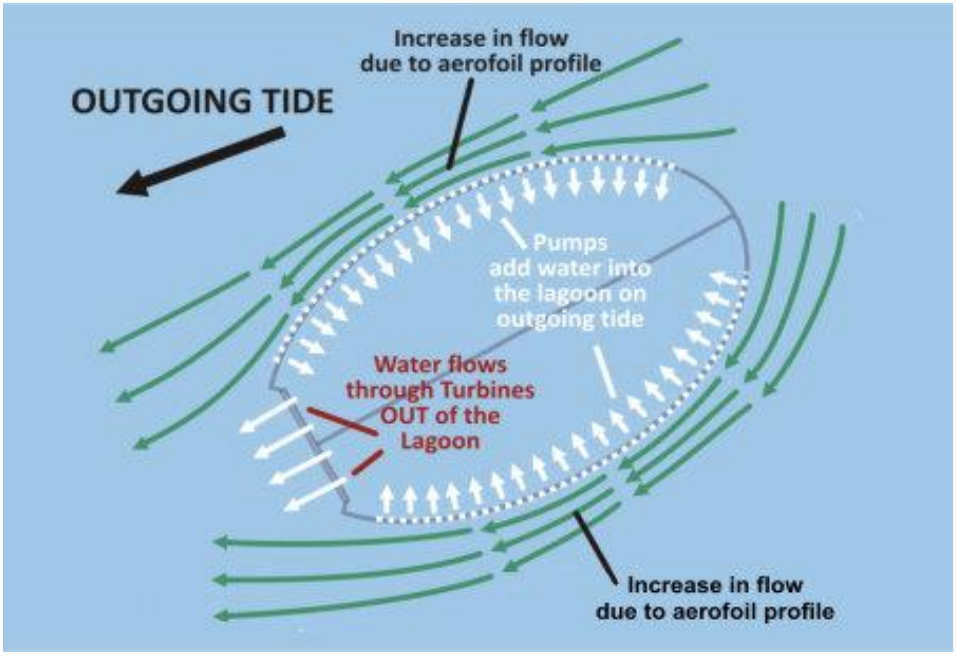


Figure 30 - Operation on outgoing tide. Source: Water Powered Technologies

The lagoon is divided in two parts so that turbine maintenance can be carried out whilst still being able to generate power (Water Powered Technologies).

Tidal streams

Tidal stream is the most advanced and successful technology used in marine energy sources, as well as in commercial terms.

There are a number of different designs for tidal stream technologies. Some of them follow the underwater wind turbine approach and some follow a hydroelectric approach to the technology. As water is denser than air, it contains more kinetic energy per square meter the turbines can be smaller than wind turbines. Realized designs are with vertical as well as with horizontal axis turbines. Devices can be mounted on the seabed or use a floating system.

Scotland, due to its large wave and tidal resources and European Marine Energy center is also home to the largest tidal turbine in the world. The Scotrenewables SR2000 device has also settled on the horizontal axis turbine design but utilizes a floating system.

Figure 31 - *The Scotrenewables SR2000, the world's most powerful tidal stream turbine. Source: Scotrenewables*

The SR2000 rated power is of 2000 kW, water current speed window from 1 to 4 m/s, two rotors with a diameter of 16 m and a variable rotor speed with fixed pitch blades.

The large scale turbine can be installed in water depths of more than 25 meters due to the flexible mooring system and can be deployed with a range of anchoring systems to suit most seabed types.

The SR2000 continues to produce excellent performance results and has delivered several other world-firsts, including demonstrating a load factor in excess of 38% in its first 24 hours of continuous generation and generating over 120 MWh in 7 days of generation with load factors in excess of 35%. During this period, the single 2MW device also generated circa 7% of the Orkney Islands electricity demand, with shorter periods exceeding 25% of demand.

Figure 32 - SR2000 Transport Model

10. Acquiring energy from tides

Answer the questions:

a) What technologies are used to derive tidal energy?

b) Using the Figure 33 indicate the regions of the world with the highest energy potential from tides.

c) What is the global potential energy of tides?

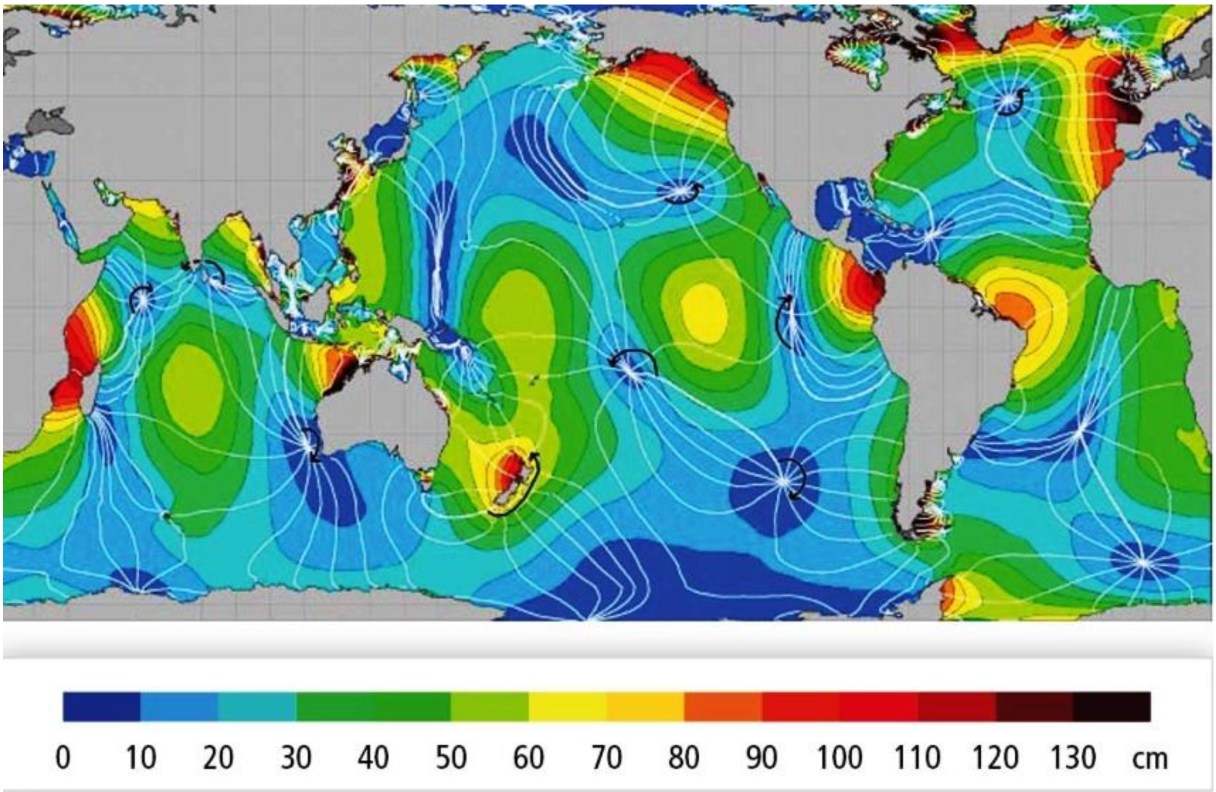
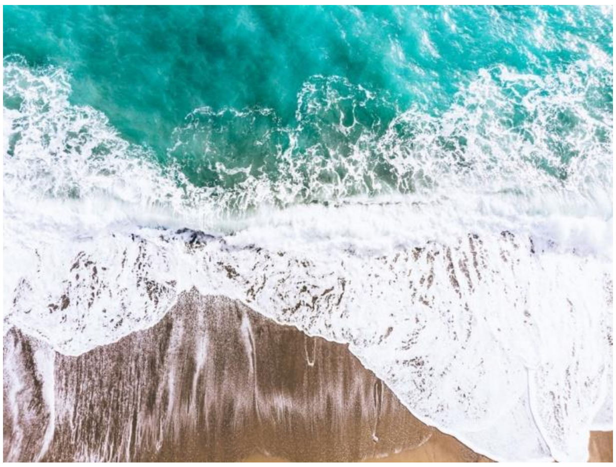


Figure 33 - Distribution of tidal rise and fall derived from gravitational forces of the Earth-Moon-Sun system.Source: Report IPCC 2012



6. What is the impact of using marine energy on environment and carbon mitigation?

Not all of the marine renewable energy can be extracted from the seas but there is so much energy in the seas even using a small percentage will be a considerable amount of energy. Marine energy is renewable, low carbon and does not take up valuable land that can be used for other uses such as growing food crops.

Marine renewable devices have less of an impact on environments compared to other technologies so long as site selections is done correctly and the design of the project is sympathetic to the location. Due to the timeline of development there hasn't been lengthy periods of time to look at device environment interaction so the "survey, deploy, monitor" approach has been taken.

Regarding tidal barrage La Rance in France, it is worth to indicate, that the beginnings of the construction of the power plant were associated with some interference in the environment, however as has been shown by ecologists' research, many years of exploitation this type of tidal power plant did not cause any side effects for the environment, and the fauna in these areas is still characterized by high diversity.

For SR2000 situation is different, and in this case turbines of this device can have negative impact on life in the ocean. So far any negative interactions are not reported.

Lifecycle analysis of marine renewable devices have assessed the environmental and climatic impacts associated with: sourcing and use of materials and energy in construction of devices, installation, operation and maintenance, decommissioning and any transport connected to the devices. Studies have shown that the greatest impact is from the amount of materials used in construction of the devices, mainly in the mooring foundations and structural components.

In most devices moorings and foundations account for more than 40% of total life-cycle greenhouse gas emissions. Total GHG emissions range from 15-105 grams of carbon dioxide per kilowatt-hour, with an average of around 53 grams. This is similar in order of magnitude to other renewables and an order of magnitude lower than non-renewable sources.

Despite the enormous potential, marine energy is used to a small extent. The contribution of marine energy to global total energy production is only 0.002% (Report IPCC 2012).

Investments of bigger scale in marine energy could be a very effective way to mitigate climate change.

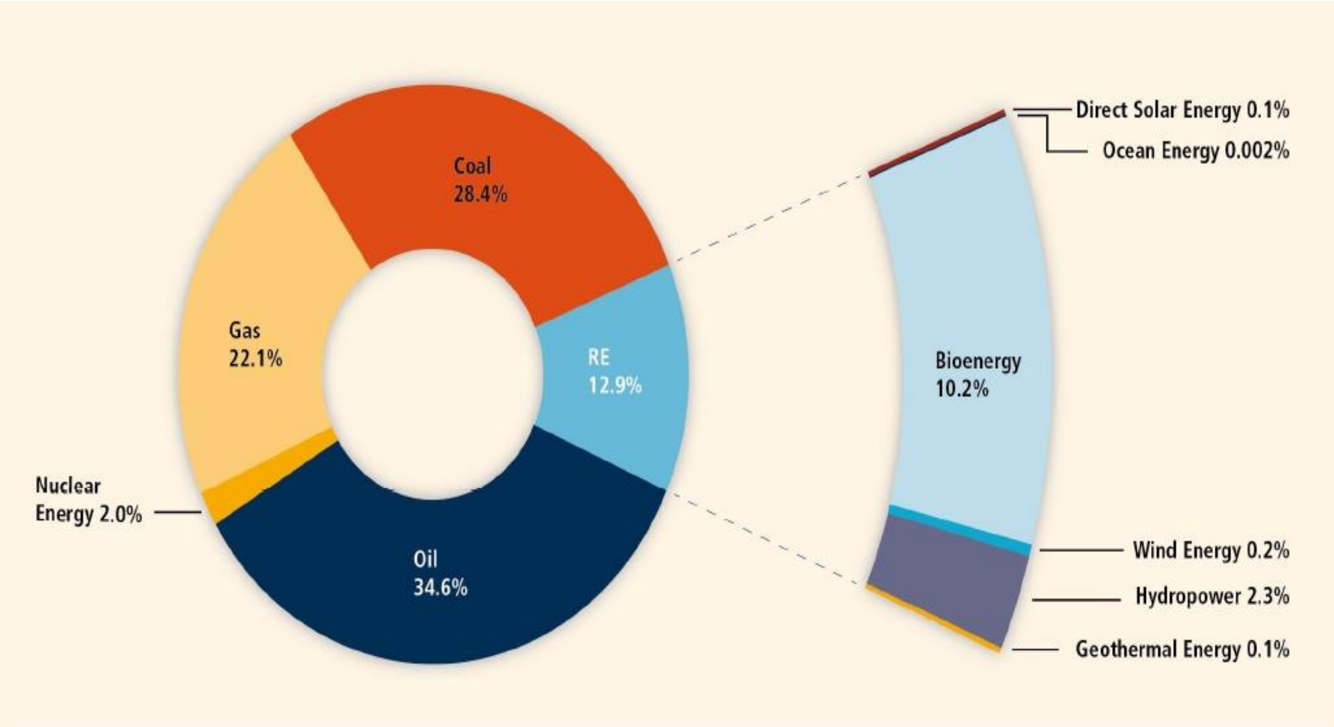


Figure 34 - Global total primary energy supply (IPCC 2008)

Economics of marine renewables

Marine energy renewable technologies are expensive. There hasn't been an electricity generation technology that wasn't expensive when it was in its infancy. All nascent technologies need time and investment to see costs reduce and government subsidy is generally the way this has been done for other generators. It's a common misconception that because marine energy isn't cheap right now, it won't be cheap in the future. If we look to other marine renewable technologies you can see that many different advances mean that the cost falls with time and scale.

Figure 35 - SR2000 in operation. The device in the picture does not flow, it is moored to the seabed. Water flow, it is tidal current (stream) we see on the picture

Final Reflections

Marine energy is clean, no carbon, but marine technologies are not. Implemented constructions during normal operation are subjected to heavy loads and also have to be resistant to the biggest storms.

This causes them to require large amounts of materials. The weight of the structure often exceeds 1000 tons. Much more material we will need for tidal barrages or tidal lagoons. Heavy transport is needed. It all generates a carbon footprint that is comparable to the carbon cost of other renewable energies.

Marine energy resources exceed the current energy needs of the whole world, and yet the share of marine energy in the total production of renewable energy is negligible. The installed capacity is only 529 MW compared to 2,18 TW of global production renewable energy (IRENA 2017).

The machines are heavy and expensive and they are designed for a specific location, with a specific sea state and local consideration conditions. Such a product can often not be used effectively in another location, which makes it difficult commercialization of production and reduction of costs and, consequently, too the lack of interested investors.

This is clearly visible in the global renewable energy investment trend. In 2016, the cumulative value of investments in marine energy reached 0.2 billion USD. For comparison, investments in solar and wind energy were appropriately allocated 113 and 112 billion USD. The global amount of investments in renewable energy has reached value USD 241 billion (IRENA).

This has its effect in the number of innovations and progress in particular types of renewable energy. The number of patents in marine energy is just over 14,000, compared to 575,323 patents submitted until 2016 (IRENA).

It seems that marine energy need bigger investment and maybe also to design smaller devices, more universal, floating rather than settled at the seabed, that can be commercially successful, for instance such as described in the current work SR2000.

We have to keep in mind that huge and inexhaustible resources of marine energy can cover much more the energy demand with a small carbon footprint. In this way, we can achieve mitigation of climate change.

11. Complete the missing words in all sentences below, according to the information previously provided in tis didactic unit.

Promising ocean technologies include:

Wave energy, whereby converters capture the energy contained in ocean …………… and use it to generate ………………... . Converters include oscillating …………….... columns that trap air pockets to drive a turbine; ……………..… body converters that use wave motion; and ……………..…… converters that make use of height differences.

…………….… energy, produced either by ……….. …………. technologies using a barrage (a dam or other barrier) to harvest power between high and low …………; tidal …………... or tidal ………………. technologies; or hybrid applications.

……… ……….. energy, arising from differing salt concentrations, as occurs where a ……………… empties into an ………………… . Demonstration projects use "pressure retarded osmosis", with freshwater flowing through a membrane to increase the …………………. in a tank of saltwater; and "reverse electro dialysis" with ions of salt passing through …………..……. membrane.

12. Marine energy and environment

Answers the questions:

a) What marine technologies are currently used to produce electricity?

b) What is the contribution of marine energy in renewable energy?

c) Is the marine energy completely clean and does not bring any carbon footprint?

d) What are the impacts of marine technology on environment?

e) Can marine energy mitigate climate change?

FINAL REFLECTIONS

Once you have developed the study related to each question, answer again to the initial questions:

1. **What types of marine energy are the most promising as sources of renewable energy?**
2. **What causes waves?**
3. **How to draw energy from the waves?**
4. **Where are the tides coming from?**
5. **How to harness tides to generate electricity?**
6. **What is the impact of using marine energy on environment and carbon mitigation**

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