ENERGY AND TELECOMMUNICATIONS

Lecture Notes

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Revision of the English version by
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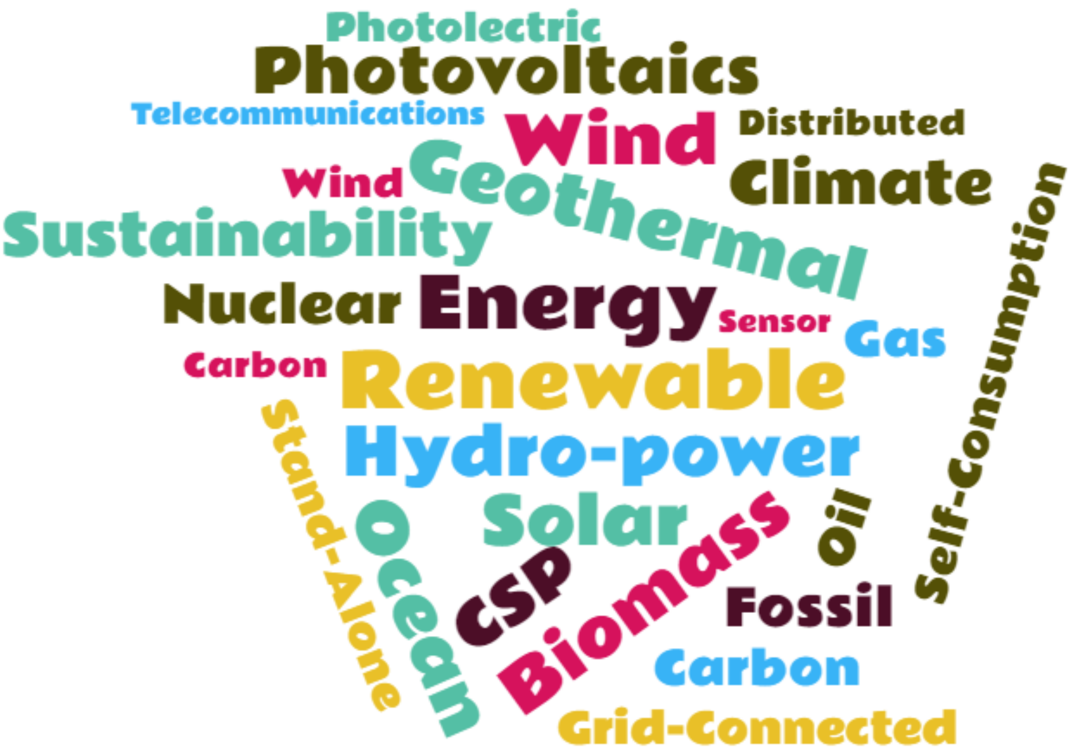
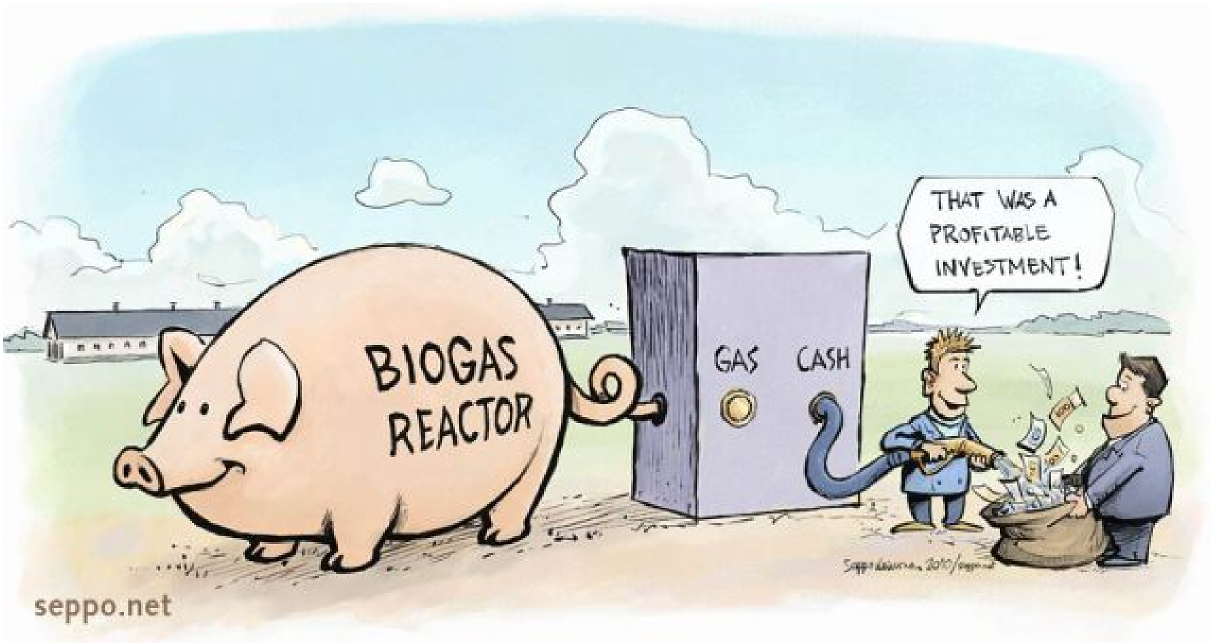


"Once the renewable infrastructure is built, the fuel is free forever. Unlike carbon-based fuels, the wind and the sun and the earth itself provide fuel that is free, in amounts that are effectively limitless."

Al Gore, former USA Vice-President and environmental activist.



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Energy and Telecommunications

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Energy and Telecommunications: Renewable Energies

Other Renewable Energies

Apart from solar and wind renewable technologies, there are other renewable energies whose fundamentals are worth reviewing. The most significant of these technologies is probably hydro-power which, although not considered a "modern" RE, exhibits remarkable figures in terms of global electricity production. Biomass, geothermal and ocean energies will be also briefly presented and discussed.

The main goals of this chapter on "other" RE are:

To understand the importance of hydro-power, as well as its fundamentals

To become familiar with the fundamentals of biomass energy

To become familiar with the fundamentals of geothermal energy

To become familiar with the different technologies derived from ocean energy and their corresponding working principles

Energy and Telecommunications: Renewable Energies

Course Structure

This course has been divided into 4 chapters devoted to an introduction to renewable energies and related concepts, solar energy (including thermal and photovoltaics technologies) and wind energy. The final chapter will be focused on other REs, such as hydro-power, biomass, ocean energies, etc.

- **Chapter 1: Introduction to REs**
  The goal is to make the student familiar with the basics of REs. This includes the understanding of the reasons that provoked the origin of these technologies, with a special focus on climate change. It is also important to have a basic knowledge of the current situation in terms of renewable energies around the world and, obviously, in our country: Spain. Which country is leader in Photovoltaics or wind energy? How has the evolution of China been in the last decade? Which is the situation of Spain now and in the foreseeable future?
- **Chapter 2: Solar Energy**
  Solar Energy can be divided into thermal and photovoltaics. We will devote little time to the former, talking about solar thermal installations (and their design) but also about CSP (Concentrating Solar Power), where the energy of the sun is converted into heat and, afterwards, into electricity. Solar Photovoltaics (PV) will be the main topic of this course, given its relevance to telecom engineers. PV basics and practical issues will be dealt with, and some grid-connected and stand-alone installation examples will be analyzed.
- **Chapter 3: Wind Energy**
  Wind energy is a well-known technology, with several installations in Spain. From a different perspective, more related to communications and sensing, this technology is also associated with the telecom industry. Wind turbine theory basics, the structure of a modern wind turbine and current technological trends will be briefly explained.
- **Chapter 4: Other Renewable Energies**
  Hydro, biomass, geothermal and ocean energies will be dealt with in this final chapter. The relevance of hydro-power for electricity production will be discussed. In addition, the fundamentals of both biomass and geothermal energy will be also discussed. Finally, the different technologies associated with ocean energy will be briefly reviewed.

Acronyms

CSP	Concentrating Solar Power
GHG	Green-House Gas
IDAE	Spanish Institute for Energy Diversification and Saving
LCOE	Levelized Cost of Energy
OTEC	Ocean Thermal Energy Conversion
OWC	Oscillating Water Column
PM	Particulate Matter
PV	Photovoltaics
RE	Renewable Energy

Symbols

F	Force (gravitational)
g	Gravitational Constant
h	Height (for hydro-power)
m	Mass (of water) (for hydro-power)
p	Power generated by moving water (for hydro-power)
T	Period
$\boldsymbol{\rho}$	Water density

Units

°C	Celsius (temperature)
J	Joule (energy)
kg/m^3	Density
kg/s	Mass Flow Rate
m^3/s	Volume Flow Rate
rpm	Revolutions per minute (rotation)
w	Watts (power)
wh	Watts-hour (energy)

Glossary

Attenuating Wave Energy Converter this wave energy device, often referred to as "marine serpent", consists of several segments. The relative movement between consecutive segments generated by the waves is used to produce electricity via power pumps or other generators.

Biomass Biomass can be understood as the organic matter that has been able to transform solar radiation into chemical energy.

Biomass Energy is the use of biomass to produce heat and/or electricity.

Direct Activation Tidal Energy refers to the use of tides to produce electricity by means of turbines usually attached to the seabed, instead of employing the alternative dam design.

Geothermal Energy refers to the use of the energy stored as heat (associated with volcanoes, hot springs, geysers, etc.) beneath the Earth's surface.

Grid Parity

Ocean Thermal Energy Conversion (OTEC) is based on the use of the different temperatures to be found at different layers (depths) in the oceans to produce electricity.

Overtopping Devices use wave energy to produce electricity by using a reservoir with a given elevation above the sea level. It will be filled with water from the waves and, afterwards, that water will go through a hole in the reservoir, thus activating a turbine. Both onshore and offshore systems can be considered.

Oscillating Water Column technology belongs to the wave energy family, where waves propel the air confined in a chamber that will move a turbine to produce electricity. This way, it is air and not water what is used to activate the turbine. In fact, the turbine is activated when the wave reaches the coast, but also when it returns to the sea.

PM (Particulate Matter) particles are a complex mixture of extremely small particles and liquid droplets that get into the air. Once inhaled, these particles can affect the heart and lungs and cause serious health effects.

Pumped Hydro Pumped hydro-power plants are based on the transportation of water from a lower elevation reservoir to a higher elevation reservoir. Afterwards, this water will be released and electricity will be produced by means of a turbine. This technology allows large-scale energy storage in the power grid.

Run-of-the-River Hydro is a type of hydroelectric generation plant where little or no water storage is provided and the course of a river is diverted to produce electricity by means of a turbine.

Tidal Energy is a kind of ocean energy that converts the energy obtained from tides into useful forms of power, mainly electricity.

Wave Activated Bodies are probably the most common wave energy devices, especially the so-called point absorber buoys. Their working principle is based on the deployment of buoys attached to the seabed and the use of wave kinetic energy to move the buoys, thus displacing an axis that allows electricity production by means of a linear generator.

Wave Energy is a form of ocean energy that converts the energy obtained from waves into useful forms of power, mainly electricity.

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Chapter 4
Other Renewable Energies

4.1. Other Renewable Energies: Introduction

Having explained the fundamentals of both solar and wind energy in this course, it could prove interesting to make a short review of other important renewable technologies such as biomass, geothermal or ocean power. Although the potential involvement of a telecom engineer in these technologies might seem less likely, we can provide a number of examples, such as the development of monitoring systems for ocean power technologies.

This chapter will therefore be devoted to briefy presenting the main concepts and relevant aspects of the following REs:

- Hydro-power
- Ocean energy
- Geothermal energy
- Biomass

4.2. Hydro-power

We should start this section by answering the following question: **Can hydro-power be considered a RE?**

To answer this question, we should refer to the definition presented in the first chapter of this course: is hydro-power obtained from natural resources that can be considered virtually inexhaustible?

The answer is YES: the water cycle on the Earth can be considered continuous, thus enabling a virtually inexhaustible resource.

Hydro-power is based on **capturing the kinetic energy of water**, converting it initially into mechanical energy and, finally, into electricity by means of a generator (turbine)[1].

[1]Conversion into electricity is common nowadays, but not required, as mechanical energy can be used to grind cereals, for example. The first water mills are described by Vitrubio (1st century), referring to those used in Persia.

Figure 4.1. Hydro-power plant in a river in Toba Montrose. Source: Alterrapower. License CC BY-SA 3.0. http://bit.ly/2GaNtnN

4.2.1. Hydro-power: Current Situation

Which are the leading countries in terms of hydro-power capacity/production? Figure 4.2 answers this question: China, Brazil, Canada and USA are the main countries in terms of installed capacity, with an accumulated global capacity of 51 %.

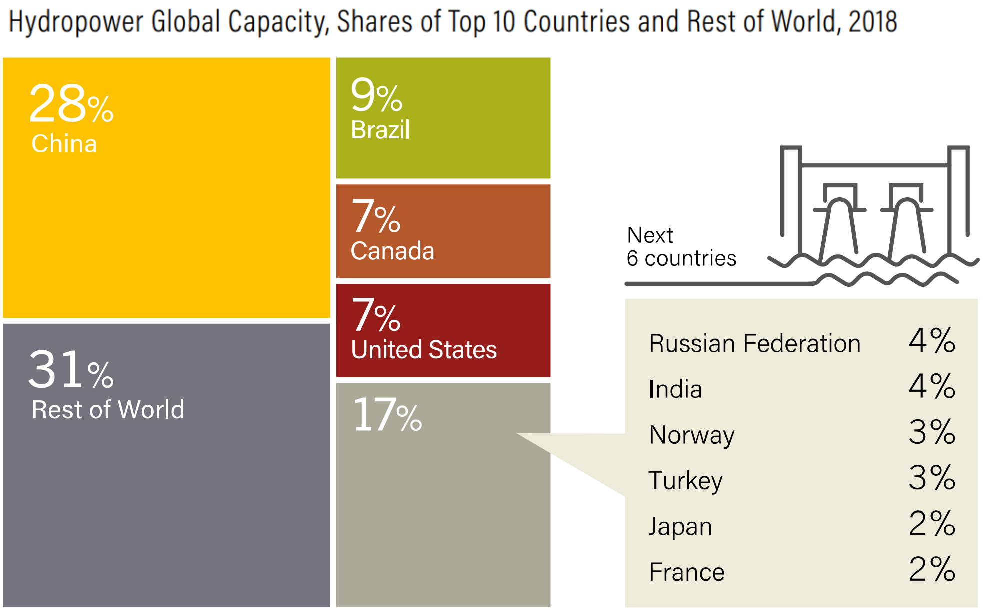


Figure 4.2. Hydro-power global capacity in 2018. Source: Renewables 2019 Global Status Report (REN21). http://bit.ly/2rTdoy3

It should be mentioned that hydro-power is a very mature technology. This explains the data represented in both Figure 4.3 and Figure 4.4. On the one hand, additions in hydro-power are relatively modest in comparison to other modern REs like solar PV or wind energy. On the other hand, this maturity helps to understand the remarkable contribution of hydro-power to electricity

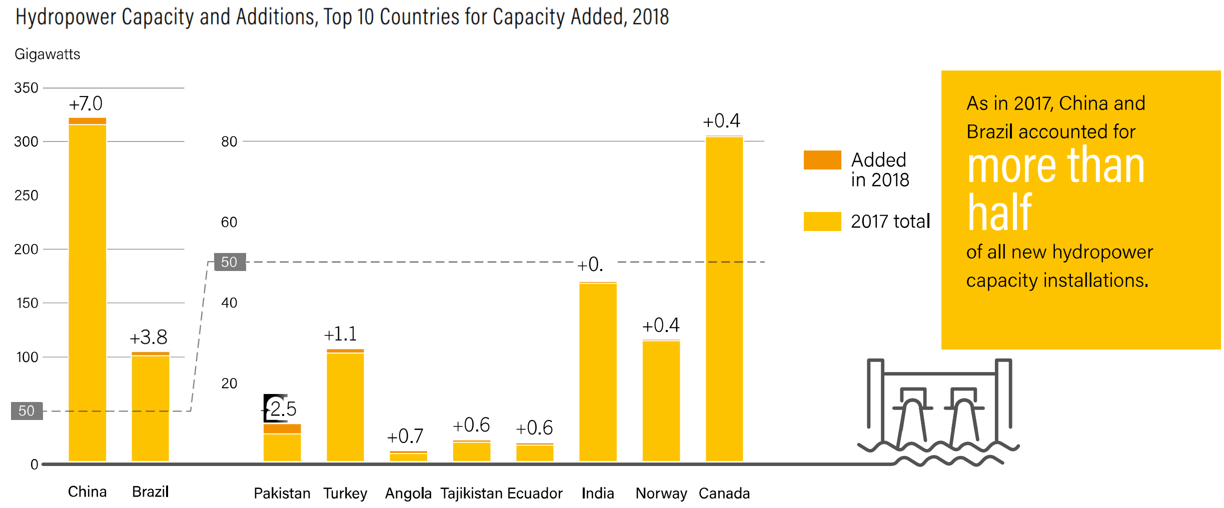


Figure 4.3. Hydro-power installed capacity and additions. Top 10 countries by 2018 additions. Source: Renewables 2019 Global Status Report (REN21). `http://bit.ly/2rTdoy3`

RENEWABLE ENERGY INDICATORS 2018

		2017	2018
INVESTMENT			
New investment (annual) in renewable power and fuels[1]	billion USD	326	**289**
POWER			
Renewable power capacity (including hydropower)	GW	2,197	**2,378**
Renewable power capacity (not including hydropower)	GW	1,081	**1,246**
Hydropower capacity[2]	GW	1,112	**1,132**
Wind power capacity	GW	540	**591**
Solar PV capacity[3]	GW	405	**505**
Bio-power capacity	GW	121	**130**
Geothermal power capacity	GW	12.8	**13.3**
Concentrating solar thermal power (CSP) capacity	GW	4.9	**5.5**
Ocean power capacity	GW	0.5	**0.5**
Bioelectricity generation (annual)	TWh	532	**581**

Figure 4.4. Renewable energies'power capacity as of end-2018. Source: Renewables 2019 Global Status Report (REN21). `http://bit.ly/2rTdoy3`

production among REs, as has been represented in Figure 4.4. Note that the total renewable power capacity (as of end-2017) is 2195 GW, whit **hydro-power contributing 1114 GW, more than 50 % of the total**.

Despite this technological maturity, hydro-power plants face challenges and update requirements. A good example are the droughts that are currently affecting many areas, thus giving rise to a significant impact on hydro production, for example in America or Southeast Asia.

Spain has also suffered from this situation, as already discussed in Chapter 1. Hydro-power was responsible for almost all the capacity additions in Spain in 2015, as the hydro-power plants of La Muela II (878 MW, Cortes del Pallás (Valencia))[1] and San Pedro II (23 MW, río Sil, Orense) started operating that year.

Both climate change effects and the greater contribution of modern REs (solar, wind, etc.) are factors that contribute to the adaption of hydro-power plants. New plants and expansions are focused on achieving higher efficiencies and flexibility, with a special emphasis on **pumped hydro**, given its special significance as a **large-scale storage solution**.

Question 2.1: Pumped Hydro

Pumped hydro has already been mentioned in the course. Briefly explain its working principle **in your own words**.

Hydro-power can be classified as follows:

- Type:
  - Dam (conventional)
  - Run-of-the-river
  - Pumped storage
- Size:
  - Large-scale > 30MW
  - Small-scale = 100 kW to 30 MW
  - Micro-hydro < 100 kW

4.2.2. Hydro-power: types of plants

The most well-known hydro-power plants are **dams**, where water is stored and then released and forced to go through a channel to a lower elevation reservoir. During this process, electricity is produced by means of a turbine.

An alternative is **run-of-the-river hydro plants**, whose working principle has been represented in Figure 4.5.

A run-of-the-river power plant works as follows:

- The water of the river is redirected by a channel
- Water is forced to go through turbines
- Electricity is produced in the associated generator
- Electricity is injected into the power grid
- Water is returned to the river

[1] When La Muela II was inaugurated in 2013, it was the largest hydro-power plant in Europe. You can view this video from Iberdrola about La Muela I and II plants: `https://youtu.be/1cq3Q1128bA`

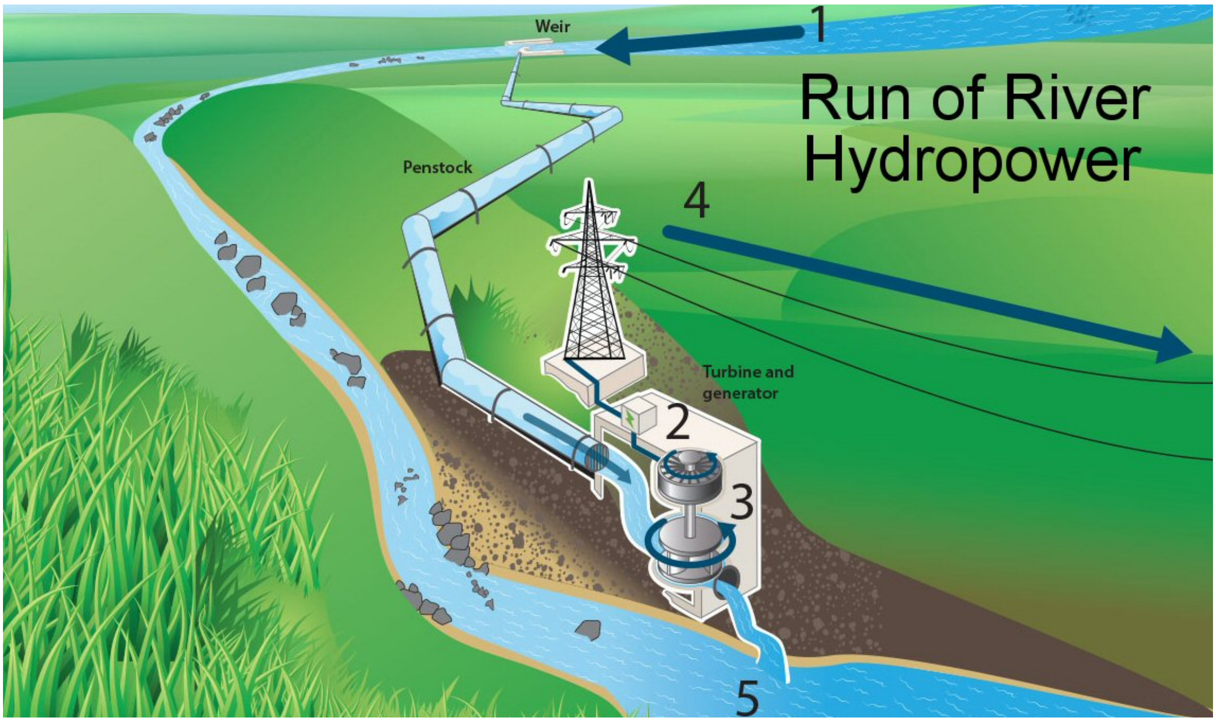


Figure 4.5. Run-of-the-river power plant. Source: `http://bit.ly/2naIlYe`

Pumped hydro plants work slightly differently. There is a lower elevation reservoir where energy is stored. Then, energy is transported to a higher elevation reservoir by means of a turbine in those periods where electricity demand is low (at night, for example). Electricity is produced then (when needed) by releasing the water of the upper reservoir, which will pass through a turbine. Thus, pumped hydro is, in fact, a **large-scale energy storage solution integrated within the power grid**. This is of particular interest within the framework of renewable energies, whose intermittent nature has been already discussed. The efficiency of these solutions, considering turbines and other factors as friction, can be estimated at around 75%.

4.2.3. Hydro-power: Additional Information

To understand the working principle of hydro-power, it is important to remember that the potential energy associated with a mass of water m located at a height h is given by mgh. The power p generated by the moving water is therefore given by the following expression, where m and V indicate the (water) mass flow (kg/s) and the water (volume) flow rate (m^3/s). ρ is the water density ($1000 kg/m^3$).

$$p = \frac{mgh}{t} = \dot{m}gh = \rho\dot{V}gh \tag{4.1}$$

A detailed analysis of turbine types is beyond the scope of this course. However, it is worth pointing out that they can be classified in to two main categories: impulse and reaction.

Impulse Turbines In these turbines, their movement is governed by water speed, and thus great

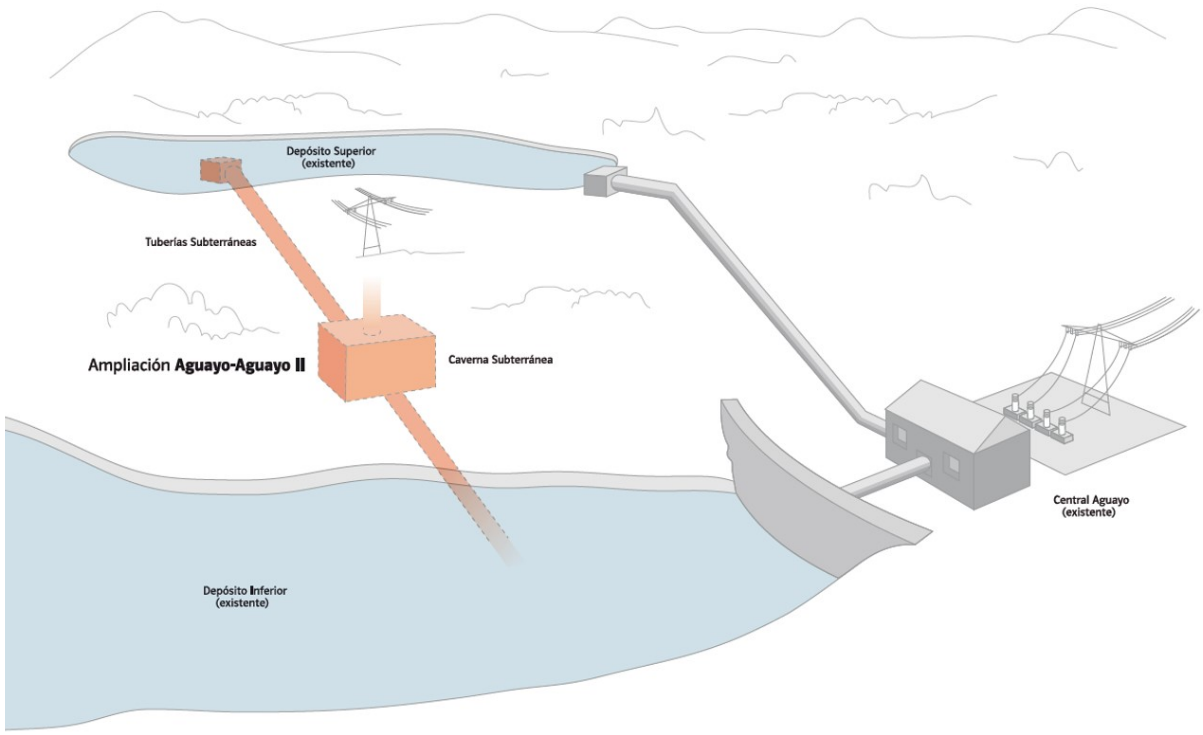


Figure 4.6. Schematic representation of the pumped hydro-power plant Aguayo II). Source: Viesgo. *Proyecto de ampliación de la central eléctrica Aguayo II.*

Figure 4.7. Turbines used in hydro-power plants. Source: (Left: Audrius Meskauskas - Own work / The rotor of the water turbine. Taken in the plant that manufactures the water turbines, Zurich); (Right: © Tamarhydro `http://bit.ly/2E4ilWi`)

heights (high heads) and low flows are recommended.

Reaction Turbines In this case energy is generated by the combined action of pressure and water movement. In this case low heads and high flows are preferred.

Important! 2.1: Hydro-Power: Turbines

More information about these turbines can be found in the following video: `https://youtu.be/k0BL0KEZ3KU`

A final thought should be devoted to the **environmental impact of hydro-power**. Even if we are talking about a renewable non-emitting energy, there are some environmental factors to be considered:

- Flooding of large areas (that could be devoted to other uses, or even considered agricultural or natural sensitive areas
- Relocation of population
- Impact on aquatic animals
- Blocking the natural course of rivers

4.3. Ocean Energies

Figure 4.8. Waves in Pacifica (California). Source: Wikimedia/Brocken Inaglory. License: CC BY-SA 4.0. http://bit.ly/1OC68IY

If you have ever been to the beach, or bathed in a river, you will have probably experienced the "power" of the sea/ocean. Tides and waves are good examples in this respect.

Ocean/Marine energies are relatively young technologies, whose relevance has increased in recent years. We are in fact talking about different technologies, although a low maturity is common to almost all of them. In fact, most of them are currently in a research and development stage and their figures in terms of capacity and generation are rather low.

Important! 3.1: Instituo de Hidráulica (Hydraulics Institute)

A well known research center devoted, in part, to the development of these Ocean energies is the Instituto de Hidráulica (Hydraulics Institute), located in Santander (Spain). http://www.ihcantabria.com/WebIH/en/

A possible classification of ocean energies could be as follows:

- Tidal Power
- Wave Power
- Ocean Thermal Energy Conversion (OTEC)

Figure 4.9 shows a comparison between conventional hydro-power technologies (also known as *Freshwater hydro*) and ocean energies. It is worth noting the huge potential of OTEC that, despite the low adoption that this technology has had to date. The only ocean energy with some commercial installations is tidal power.

Table 8.2 Relative Sizes of Some Various Hydro Resources

Energy Source	Potential (GW)	Practical (GW)	To Date
Freshwater hydro	4,000	1,000	654
Waves	1,000–10,000	500–2,000	2.5
Tides	2,500	1,000	59
OTEC	200,000	10,000	0

Source: Tester, J.W. et al., *Sustainable Energy: Choosing among Options*, The MIT Press, Cambridge, MA, 2005.

Figure 4.9. Comparison between freshwater hydro and ocean energies (potential and installed capacity). Source: Renewable Energy: A First Course (Robert Ehrlich)

A brief review of tidal, wave and ocean thermal energies is given in the following sections:

4.3.1. Tidal Energy

Tides are periodic (and predictable, as they depend on the relative position of the Earth, Moon ... and Sun!) variations of sea and ocean levels. This phenomenon can be explained using **Newton's law of universal gravitation**[1], taking into account the gravitational forces that the Moon and Sun exhibit on the Earth. Tides depend on the inverse of the cubed distance between the Earth and the Moon/Sun. To find the corresponding expression, it is only necessary to apply Newton's law and determine the gravitational force of the Moon upon the Earth:

$$F = \frac{gMm}{r^2} \tag{4.2}$$

From this equation, it is easy to derive:

$$F_x = \pm\frac{2gMmR}{r^3} \tag{4.3}$$

[1] http://bit.ly/2fKxvW9

$$F_y = \pm \frac{gMmR}{2r^3} \tag{4.4}$$

In these equations, g is the gravitational constant, M the mass of the Earth, m the mass of the Moon, r the distance between the Moon and the Earth and R the Earth's radius.[1]. F_x indicates the opposite forces that act on the opposite sides considering the Earth's axis to be the line that connects it to the Moon. This will imply an "enlarging" effect of the Earth, while F_y would imply a "compression" of the axis orthogonal to x.

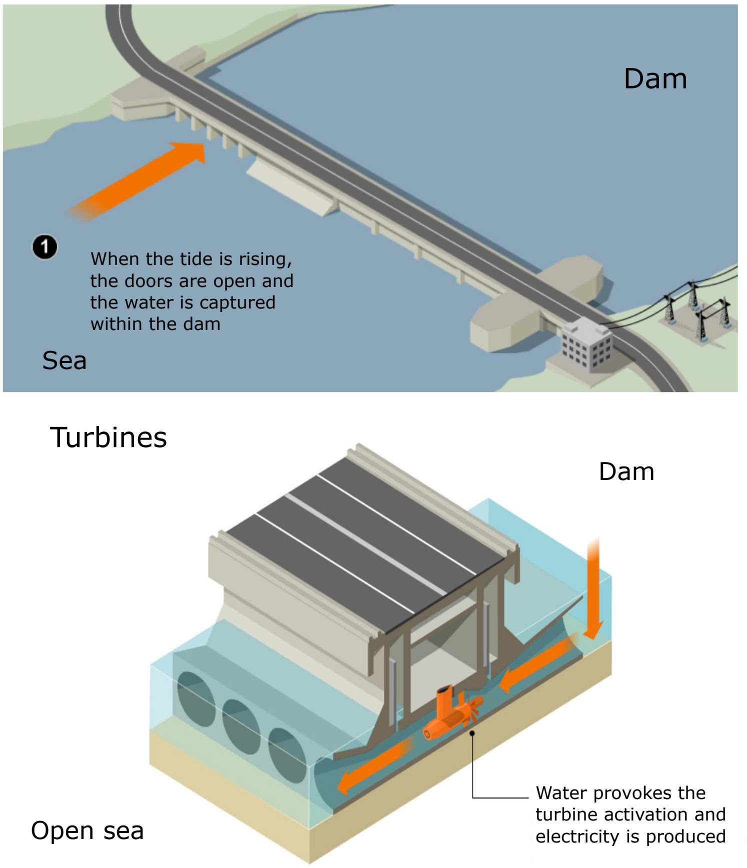


Figure 4.10. Scheme of a tidal power plant. Source: Consumer.es `http://bit.ly/1qsdtw0` (License for teaching purposes.)

There are **two main strategies** for the exploitation of tidal energy: by means of **dams or by the direct activation of turbines**. The global potential of this renewable energy is estimated to be 3000 GW, although a small percentage (let's say around 3 %) would be at locations suitable for its exploitation.

An important limitation of this technology is the difficulty in finding **suitable locations**, as the difference between the level for low and high tides should be above 5 meters, at least. Some of the best global locations have been indicated in Figure 4.11. Usually, these best locations are tidal rivers, bays and related places, where the construction of a dam is feasible. It is interesting to note

[1]A more detailed explanation can be found in the book "*Renewable Energy: A First Course*" de Robert Ehrlich.

that the average tidal difference is about 1 meter, although the best known location is probably Fundy Bay (Canada) with 16-20 meters.

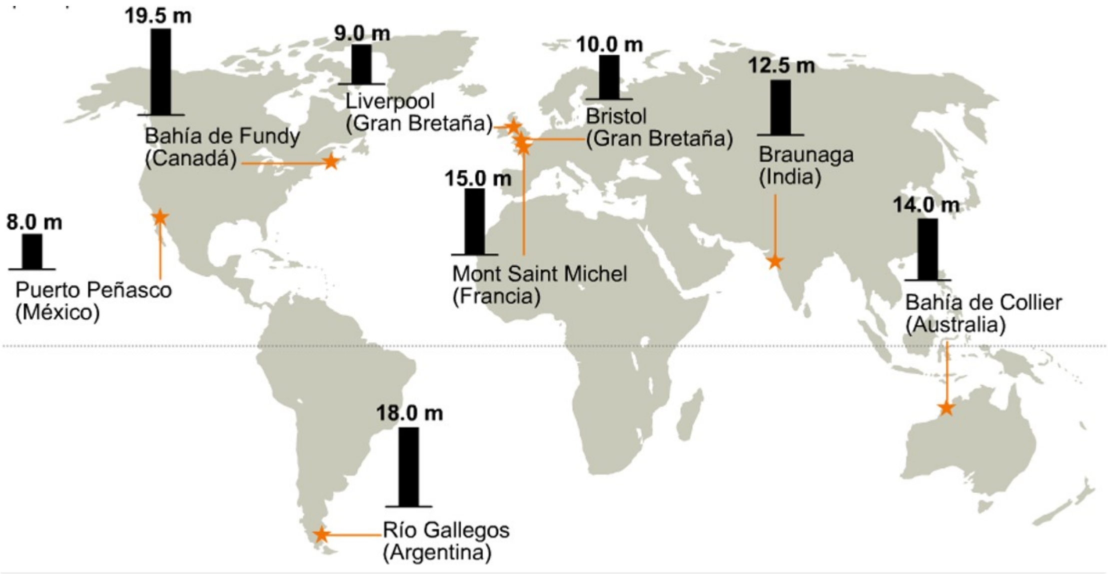


Figure 4.11. High potential areas for tidal resources. Source: Consumer.es http://bit.ly/1qsdtw0 (License for teaching purposes.)

The **tidal power plant located on the Rance river (Bretagne, France)**[1] (see Figure 4.12) is the best worldwide example of this technology. It began its operation in 1966 and is formed by 24 turbines with 10 MW generators. It is a reversible plant, as it works in both directions (when the dam is filled and emptied). The LCOE of this plant is supposed to be similar to that of conventional plants, although the **environmental impact was significant**, affecting for example the salinity of the river and, consequently, its animal life.

Tidal power plants based on dams like the one located on the Rance river are not the only possibility for extracting energy from tides. The **Direct activation of turbines** is also being investigated, with some similarities to wind turbines. A good example is the **Lanstrom turbine** shown in Figure 4.13, with a rotor diameter of 20 meters and fixed to the seabed. These turbines are manufactured by the Norwegian company Andritz Hydro Hammerfest, which installed its first turbines in 2003[2].

[1] http://bit.ly/1GLZQ8g

[2] The installation process of these turbines is shown in this video: https://youtu.be/cHExRbCdTck

Figure 4.12. Rance river tidal power plant. Source: Wikimedia / Dani 7C3. License: CC BY-2.5 http://bit.ly/1GLZQ8g

Figure 4.13. Installation of a Lanstrom turbine. Source: Andritz Hydro Hammerfest (hammerfeststrom). License: YouTube standard https://youtu.be/cHExRbCdTck

A similar approach, although with a different design, is found in **Seagen turbines**, manufactured by Siemens. They are supposed to be the first commercial direct activation turbines produced on a global scale (2008). Each system is equipped with 2 turbines, summing up a total capacity of 1.2 MW. Some units have been installed in Northern Ireland[1].

A different solution is proposed by the **Vivace system**, whose operation is based on the turbu-

[1] The working principle of these turbines is explained in the following video: https://youtu.be/AfGRBFdw2_g

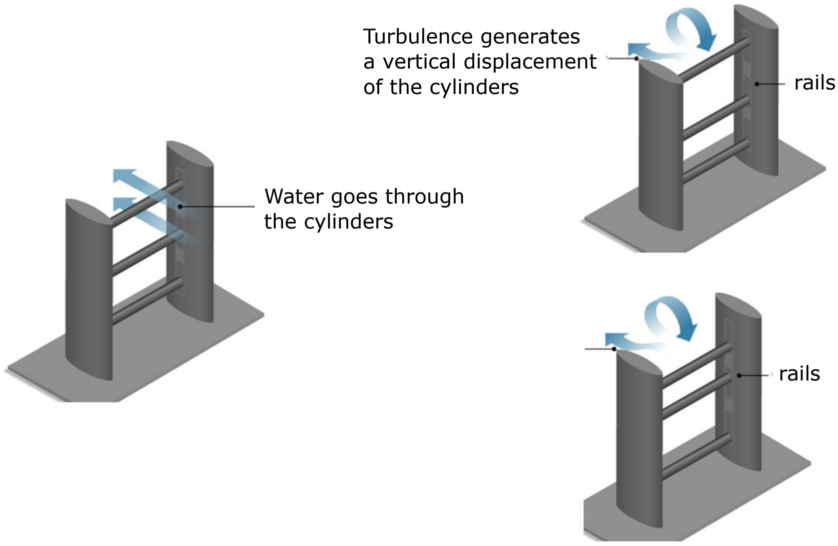
lence generated by marine currents that go through cylinders, as shown in Figure 4.15. The top of the figure shows the working principle of this device, and the bottom shows a test performed in the laboratories of Michigan University[1].

Having presented some examples of tidal energy, it is now time to analyze the pros and cons of these technologies:

Pros	Cons
No CO2 emissions	Limited potential locations
Predictable	Long distances to the power grid
Low flow speeds	Production limited to 40 days/year
Efficiencies ≈ 80 %	Environmental Impact
Low operation costs	Component deterioration
Lifetime ≈ 75/100 years	Visual impact

Figure 4.14. Seagen turbine. Source: Marine Current Turbines Limited http://bit.ly/2E8RVTr

[1] A video of this test can be found here: https://youtu.be/IcR8HszacOE



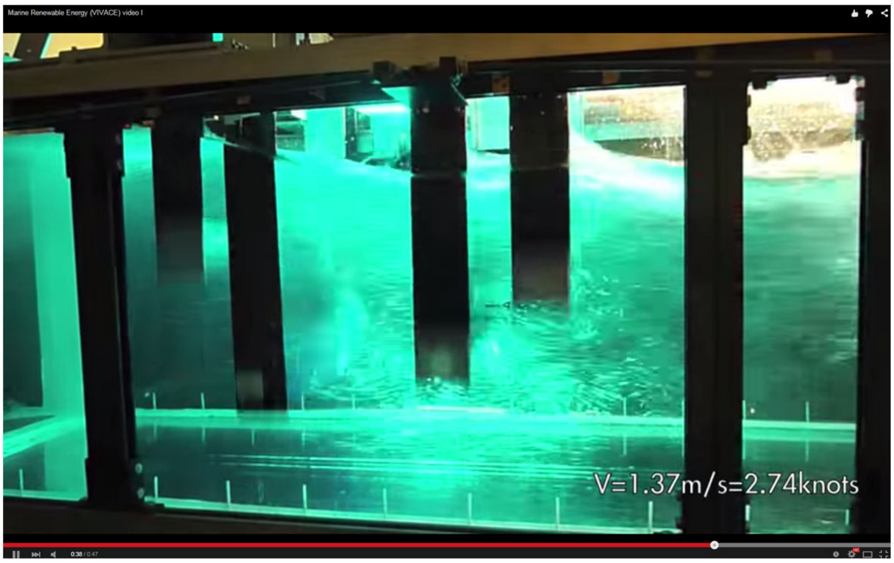


Figure 4.15. Vivace tidal system. Source: (Top: Consumer.es http://bit.ly/1qsdtw0); (Bottom: UMVIVACE. License: YouTube standard. https://youtu.be/IcR8HszacOE

4.3.2. Wave Energy

Wave energy is based on the use of the energy associated with waves. Waves are created by the wind that blows over the ocean/sea surface. There are many places around the world where waves are constant enough so as to produce energy continuously. Some estimations indicate that the potential of wave energy could be around 140 to 750 TWh/year. Figure 4.16 shows the conclusions of a study performed to evaluate wave energy potential. The average power density has been indicated for each location.

To better understand Figure 4.16, it is important to know the expression that allows estimating the power of a given wave:

$$P_{avg} = \frac{\rho g^2 T H^2}{8\pi}$$

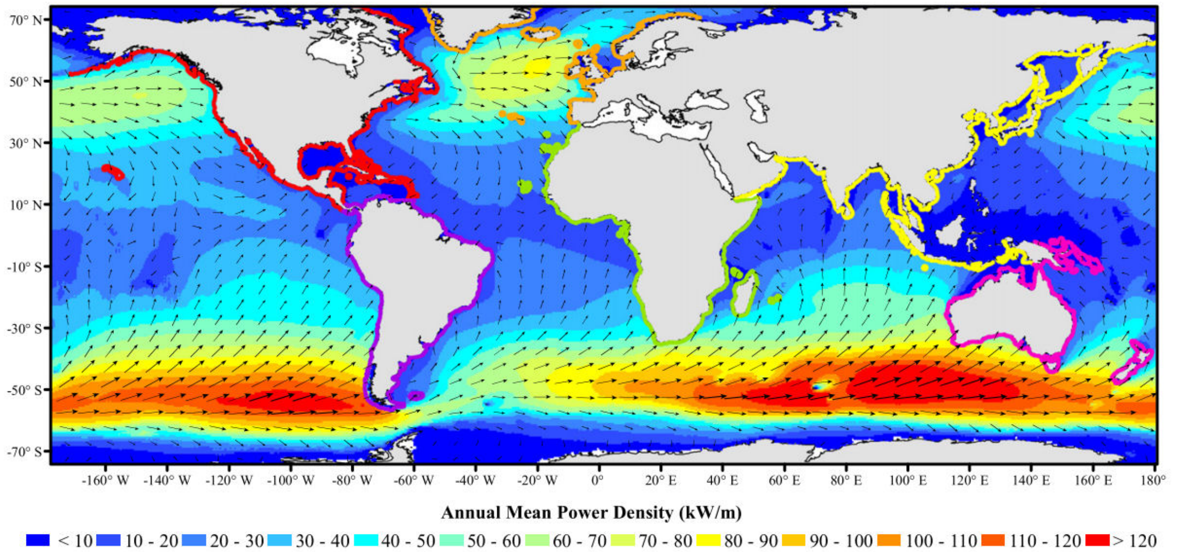


Fig. 1. Annual mean wave power density (colour) and annual mean best direction (→). The land buffers used to quantify the resource are also shown, coloured by continent (see Section 3). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Figure 4.16. Average power density (kW/m) (annual) associated with wave energy (arrows indicate prevalent wave directions). Source: Gunn y Stock-Williams (2012) *"Quantifying the global power wave resource"*. `http://bit.ly/2DL7mU4`

As can be appreciated, the power of a wave is directly proportional to its squared height (H) and its period (T) (ρ is the water density ($1025 kg/m^3$)), and g acceleration due to gravity ($9{,}81 m/s^2$).

Important! 3.2: Wave Power

In a storm, waves can easily reach 10 meters (not necessarily close to the coast) every 15 seconds. Using the above equation, and considering a water density of $\rho = 1025 kg/m^2$, the associated power will be P = 5.9MW.

Within wave energy, there are different devices that can be used to generate electricity. A typical classification is shown in Figure 4.17.

Wave activated bodies

Wave activated bodies are probably the most common wave energy devices, especially the so-called **point absorber buoys**. Their working principle is based on:

- The deployment of buoys attached to the seabed
- Wave kinetic energy that moves the buoys, thus displacing an axis that allows electricity production by means of a linear generator

Figure 4.18 presents a point absorber buoy installed in Santoña (Cantabria): the buoy has a power pump that transfers the mechanical energy to an alternator, whose current is afterwards

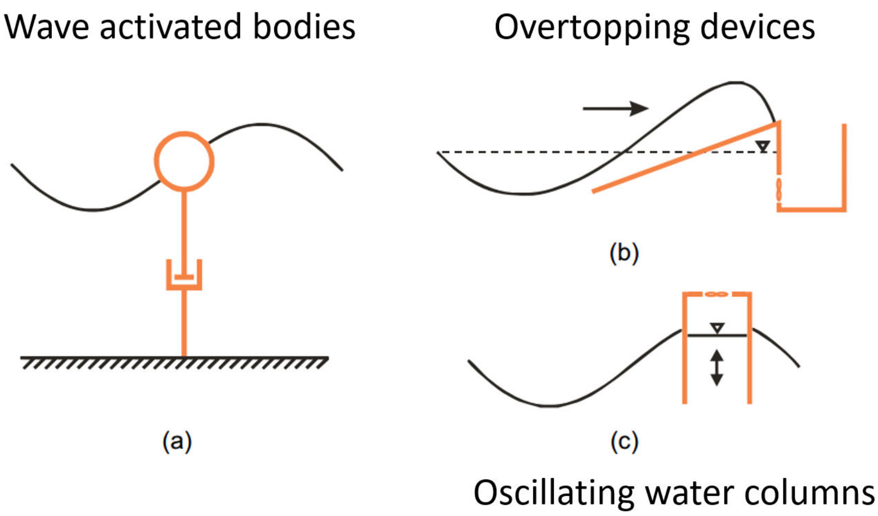


Figure 4.17. Wave energy technologies: a) Wave activated bodies, b) Overtopping devices and c) Oscillating water columns.

Figure 4.18. Point absorber buoy installed in Santoña (Cantabria). Source: Europapress http://bit.ly/2DBFuhC

injected into a power cable. Its capacity is 40 KW and it is an experimental device used to analyze the feasibility of a larger deployment.

An alternative wave energy solution is based on an **attenuating wave energy converter**. Figure 4.19 shows a photo-montage of a wave energy "plant" (left) and a picture of a Pelamis model (right). As can be observed, this device is made up of several segments. The relative movement between consecutive segments generated by the waves is used to produce electricity via power pumps or other generators[1]. The Pelamis design favors the durability of the device over its efficiency, as it is supposed to be deployed in locations with extremely bad weather conditions.

[1]In the following video, the working principle of these devices is explained: https://youtu.be/mcTNkoyvLFs.

Currently deployed systems are fundamentally for experimental purposes.

Figure 4.19. Attenuating wave energy converters: a) Pelamis wave energy plant (Source: Jumanji Solar (Flickr) http://bit.ly/2DHM9dE, b) Pelamis device tested in EMEC (European Marine Energy Test Centre) (Source: Wikimedia http://bit.ly/2rDoZjU (License: public domain)).

Overtopping devices

The working principle of **overtopping devices** is very simple (see Figure 4.20). The idea is to develop a reservoir with a given elevation above sea level. It is filled with water from the waves and, afterwards, that water will go through a hole in the reservoir, thus activating a turbine. Both onshore and offshore systems can be considered.

Wave Dragon is one of the main examples of these devices. It is commercialized by a Danish company and was developed by a European consortium with participants from Austria, Denmark, Ireland, Portugal, Sweden and the UK. The first prototype was connected to the Danish (Nissum Bredning) power grid in 2003. More information about the Wave Dragon can be found at: http://bit.ly/2nbmz7g.

Oscillating water columns

Wave energy can also be used in installations deployed on the coast, the so-called **oscillating water columns** (OWC). Waves propel the air confined in a chamber (see Figure 4.21) that will move a turbine to produce electricity. This way, it is air and not water that is used to activate the turbine. In fact, the turbine is activated when the wave reaches the coast, but also when it returns to the sea.

There is an OWC system deployed in Mutriku (País Vasco)[1]. A lab-test of this device is presented in this video: https://youtu.be/mVQ3ZT1i_Hs.

Question 3.1: Oscillating Water Columns

What is your opinion about OWC? Do you think that this is a mature technology? Which turbines are used in these devices?

[1] http://bit.ly/2E8HS0k

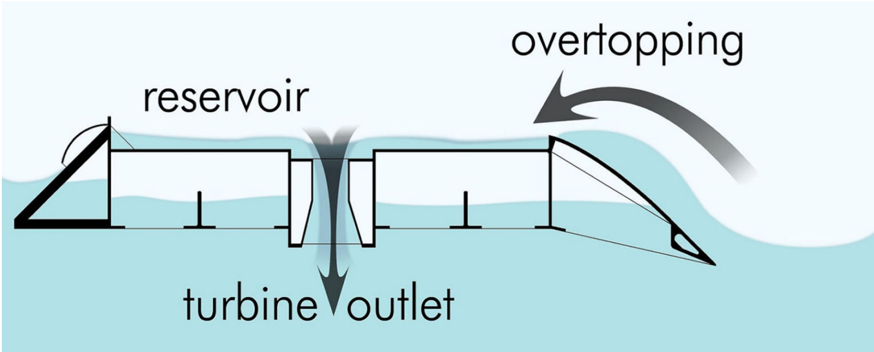


Figure 4.20. Overtopping device: a) Working principle (top); b) Wave Dragon (example of overtopping device) (bottom). Source: Erik Friis-Madsen / License: Creative Commons Attribution 3.0 Unported (top and bottom).

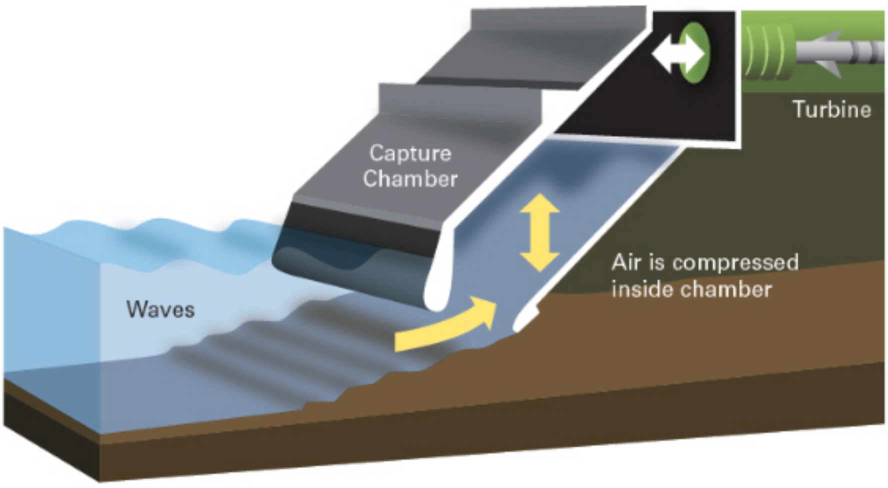


Figure 4.21. Oscillating water column. Source: UIOWA Wiki `http://bit.ly/2nb1HMR`

OTEC: Ocean Thermal Energy Conversion

Oceans cover around 70% of the Earth's surface. Solar radiation captured by the oceans is equivalent to 600 times the global demand. Consequently, if we were able to use the thermal energy captured by the oceans, a potentially huge capacity would be at our disposal.

OTEC is based on the different temperatures to be found at different layers (depths) in the oceans. The following layers are typically considered:

- Surface layer: with a thickness from 100 to 200 meters, it works as heat collector, with temperatures from 25 to 30 °C
- Intermediate layer: from 200 to 400 meter depth, it exhibits a fast temperature variation and acts as a thermal barrier between the surface and deep layers
- Deep layer: where temperature decreases to 4 °C at 1000 m and 2 °C at 5000 m

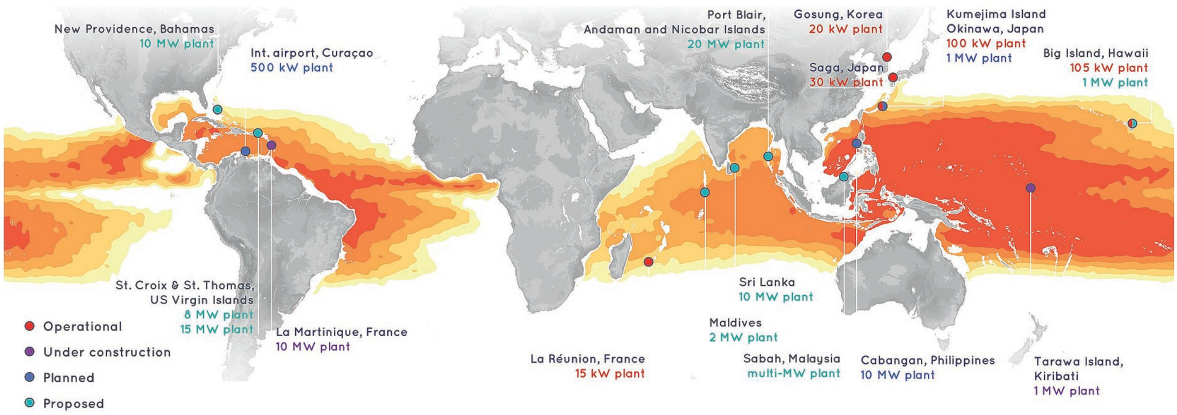


Figure 4.22. OTEC potential locations. Source: Wikimedia. License: CC BY-SA 4.0. http://bit.ly/2DCvTv5.

Coastal areas in the tropics offer high temperature gradients, as represented in Figure 4.22, where the currently operational installations (or those planned for future years) have also been indicated.

Figure 4.23 shows the working principle of OTEC, which is based on the so-called Rankine cycle. A fluid, ideally with a boiling point lower and a vapor pressure higher than water, is used to activate a turbine. The water heated at the ocean surface is pumped into a heat exchanger, where heat will be transferred from the sea water to the chosen fluid. The latter will be evaporated, thus activating the turbine. The cooled sea water will be transported to a second heat exchanger, where vapor will be condensed to a liquid state for its reuse.

It is worth noting that, as suggested, water is not the most suitable fluid for these systems. Ammonia is far better for the above mentioned reasons. If water is used, the system is an **open-cycle OTEC**, while a **close-cycle OTEC** refers to systems employing ammonia. The latter indicates the necessity of confining the ammonia within the system, due to the serious environmental impact that could be caused.

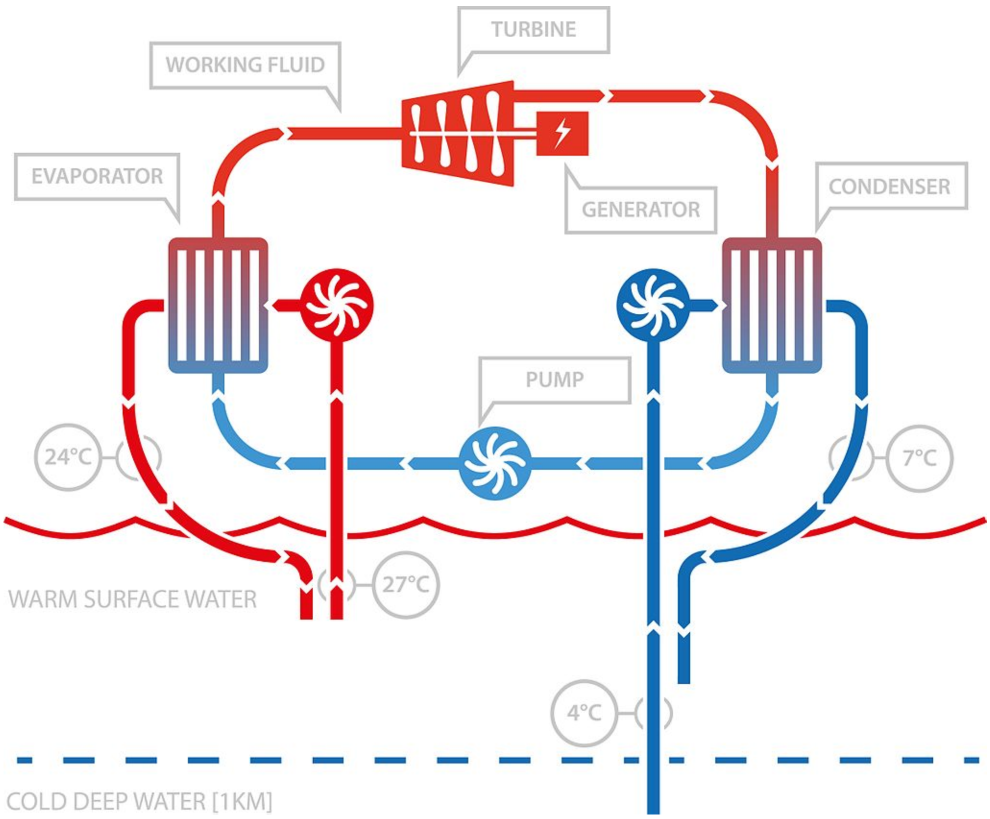


Figure 4.23. Working principle of an OTEC plant. Source: Wikimedia. License: CC BY-SA 4.0. http://bit.ly/2DyHDdX.

The potential of OTEC is remarkable, but it is not clear if a significant development will be achieved in future years. Current efficiencies are low due to its low maturity, which also implies high LCOEs. Current plants exhibit production in the KW range, while future OTEC systems are expected to increase to the MW range.

Question 3.2: Fluids and Boiling Points

Regarding open and close cycle OTEC systems: do you know what the boiling points of water and ammonia are? Is it possible to modify the temperatures associated with these boiling points?

4.3.3. Ocean Energies: Evolution and Forecast

Having presented the fundamentals of ocean energies, it would be very interesting to analyze the forecasts of these systems. There is a fantastic study in the IDAE report entitled *"Evolución tecnológica y prospectiva de costes de las energías renovables"*[1]. Figure 4.24 (from this report) relates generation costs to technological maturity. Obviously, when a technology is in its early stages (experimental, research and development), generation costs will be high. However, as this technology evolves toward a more mature stage, these costs will be significantly decreased.

[1] [Technological evolution and cost prospective of REs] http://bit.ly/2nRALmR

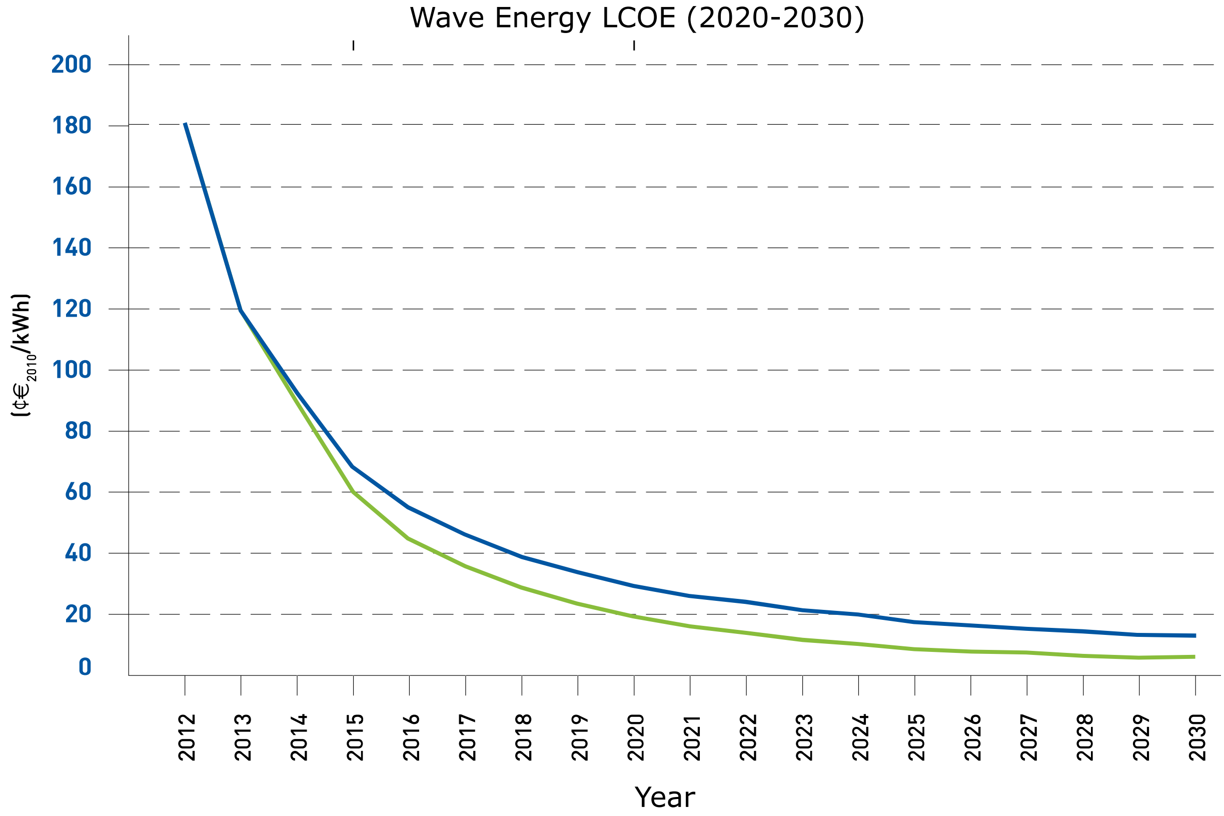


Figure 4.24. Forecast of the generation cost evolution for wave energy. Source: IDAE *"Evolución tecnológica y prospectiva de costes de las energías renovables"* `http://bit.ly/2nRALmR`.

Three phases have been represented in terms of technological maturity (this particular case concerns wave power, but it could be perfectly extrapolated to any other RE):

Reliability confirmation: The achieved technological development does not allow conclusions to be made about lifetime, efficiency or generation cost.

Take-off: Where lifetime and efficiency improve and generation costs decrease towards grid parity.

Consolidation: Lifetime and efficiency come close to their expected values

4.3.4. Levelized Cost of Energy: LCOE

The concept of LCOE was already introduced in the first chapter of this course. Some graphs were also discussed in Chapter 2; however, data regarding the LCOE of ocean energies don't appear in these reports[1]. This is due to their lack of maturity, which gives rise to very high LCOEs.

Figure 4.25 is specifically focused on ocean energies and it can be appreciated how all these technologies, **with the only exception of tidal energy**, are in low stages of maturity. For example, wave power is currently dealing with several buoy designs, in an attempt to find the most suitable devices for development in the near future.

[1] See for example: Renewables 2018 Global Status Report (REN21). `http://bit.ly/2T1tWKU`

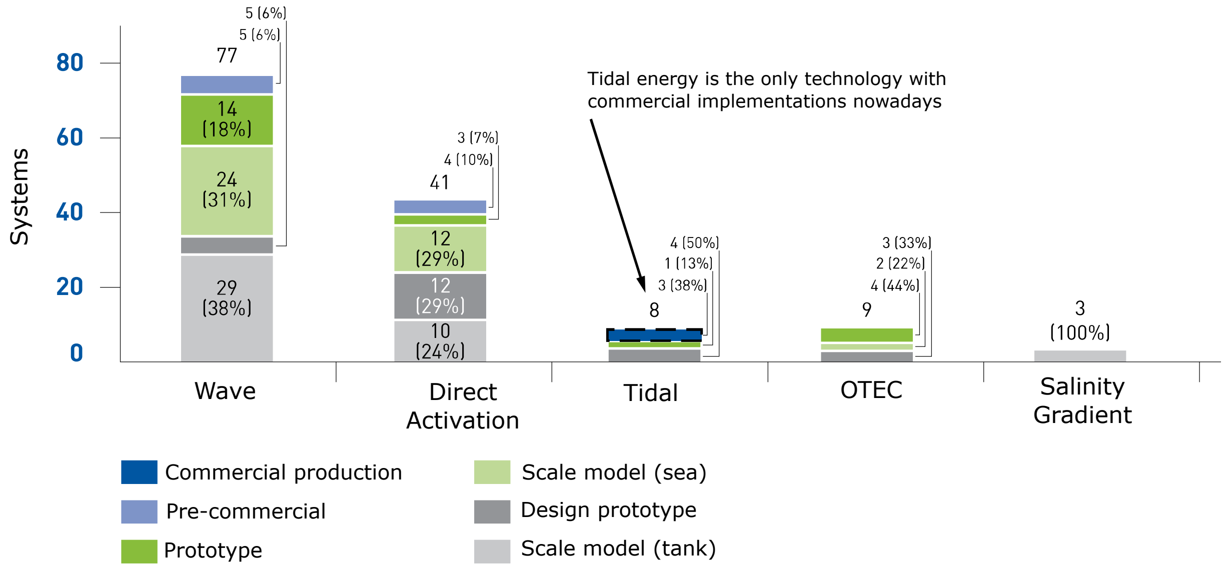


Figure 4.25. Technological maturity of ocean energies. Source: IDAE *"Evolución tecnológica y prospectiva de costes de las energías renovables"* `http://bit.ly/2nRALmR`.

Question 3.3: Salinity Gradient

In Figure 4.25, a new technology appears: **Salinity Gradient**. As it has not been mentioned in the course, look for information about it and explain, **in your own words**, the working principle of this technology. Also comment on the technological maturity of this technology and current projects.

4.3.5. Ocean Energies: Pros and Cons

Ocean energies exhibit some clear advantages, like their non-emitting nature or the absence of noise. Moreover, islands are normally complicated locations in terms of power grid energy distribution, however they are perfect locations for the development of these systems.

As disadvantages, these projects usually imply visual and environmental impacts, affecting animals. Technological maturity is, generally speaking low, thus currently giving rise to high LCOEs. Finally, these systems have to be deployed in very harsh environments, given the effect of sea water on electronics, metallic structures and so on.

Pros	Cons
Renewable	Visual and environmental impact
Non-emitting	Impact on animals
Silent	Limited power
Suitable for islands	High LCOEs
	Complicated maintenance
	Low maturity

Question 3.4: Wave Power: Problems

Let's assume that you are an engineer working for a company interested in the development of wave power systems. You are asked to write a list of possible problems derived from the installation and maintenance of a wave power system. Draw up this list with as many entries as possible.

4.4. Geothermal Energy

Geothermal Energy refers to the use of the energy stored as heat (associated with volcanoes, hot springs, geysers, etc.) beneath the Earth's surface. This is one of the few REs that is not directly related to the Sun as an energy source, as geothermal heat has its origin in radioactive isotopes, in the movement of the surface layers of the Earth and in the latent heat coming from inner core crystallization.

Taking into consideration the entire surface of the Earth, the available potential geothermal energy is $4.2\cdot10^{1}2$ J. This is obviously a huge amount of energy, but only a small fraction can be collected by us. The geothermal resource is, therefore, the heat fraction that, coming from the inside of the Earth, can be used by us for different purposes, for example electricity production.

Figure 4.26. Geothermal power plant in Iceland. Source: Wikimedia / Gretar Ivarsson – Edited by Fir0002 - Gretar Ivarsson, geologist at Nesjavellir. The Nesjavellir Geothermal Power Plant in Þingvellir, Iceland. License: Public Domain `http://bit.ly/2nJVk0v`

4.4.1. Geothermal Energy: a brief History

Geothermal energy has been used for many centuries. Bath, for example, a city located in South West England, was named after the baths built by the Romans. However, it was only in the 20th century when the potential of this energy source was exploited for electricity production. In 1904 the first geothermal plant was built. The Larderello geothermal plant (Northern Italy, close to Pisa and Florence) was built in 1911 (see Figure 4.27).

Figure 4.27. Larderello geothermal plant in 1913. Source: manodemandiocaambiente.blogspot.com.es `http://bit.ly/2DH8dG8`

Important! 4.1: Larderello Geothermal Plant

More than 100 years later, the Larderello Geothermal plant is still working, operated by Enel and with an estimated 10% of the global geothermal power capacity (4800 MW).

In terms of its use, high temperature geothermal resources are often used to produce electricity, with temperatures above 100-150 $°C$). For resources with lower temperatures, heating applications are considered.

4.4.2. Geothermal Power Plants: Types

Electricity generation by means of geothermal power is carried out in 3 different types of power plants: dry steam, flash and binary cycle.

Dry steam power plants are probably the less common of the three. In this case, the vapor required to activate the turbine comes spontaneously from the well, thus locations with very high temperature gradients are required.

Flash power plants are based on the use of high-pressure water pulled from the well. This water is vaporized as the pressure decreases and the resulting vapor is used to activate the turbine. This is probably the most common geothermal power plant.

Finally, **geothermal binary cycle** power plants use an intermediate stage, with a heat exchanger where vapor is generated at lower temperatures.

Apart from electricity production, it is worth mentioning that geothermal energy can also be used for heated water and heating in homes and buildings.

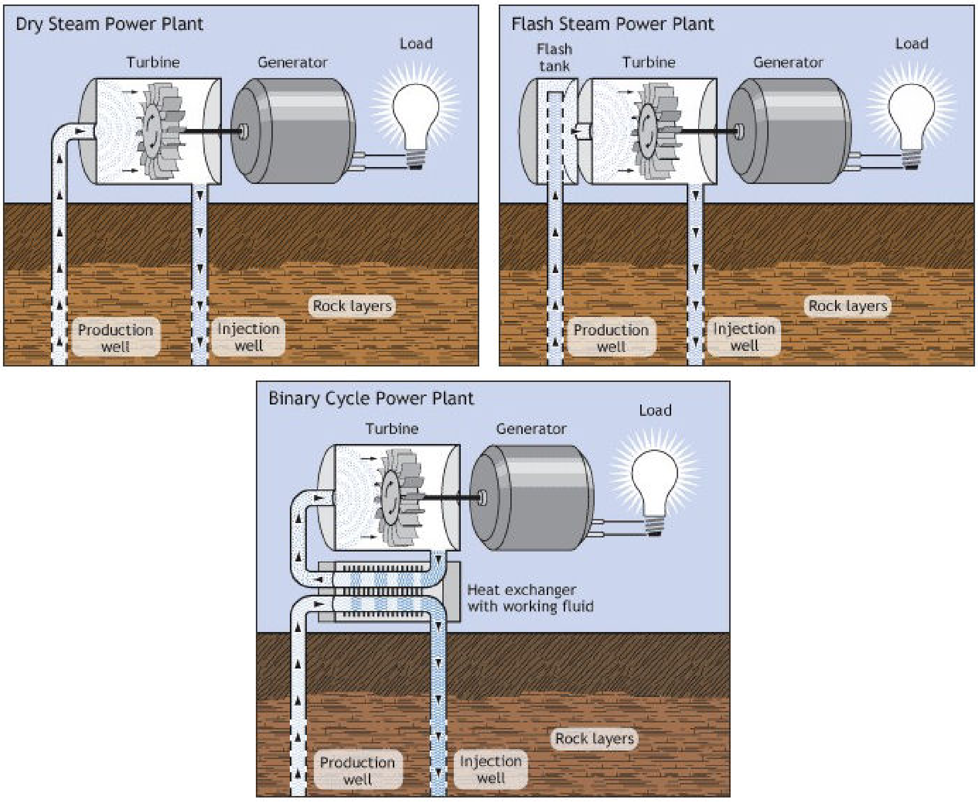


Figure 4.28. Geothermal power plants: types. Source: energyalmanac `http://bit.ly/1N50wjm`

4.4.3. Geothermal Energy: Locations

There are not suitable geothermal locations everywhere and, unlike other renewable sources like solar and wind energy, in this case it is necessary to "extract" the resource, as it is initially "hidden" from us. In Spain, for example, suitable geothermal locations are mainly located in Andalucia and the Canary Islands.

Normally, the excavation of a well is required to evaluate the temperature and determine whether or not the location is suitable. In addition, other techniques can also be employed:

- Satellite/airborne imaging

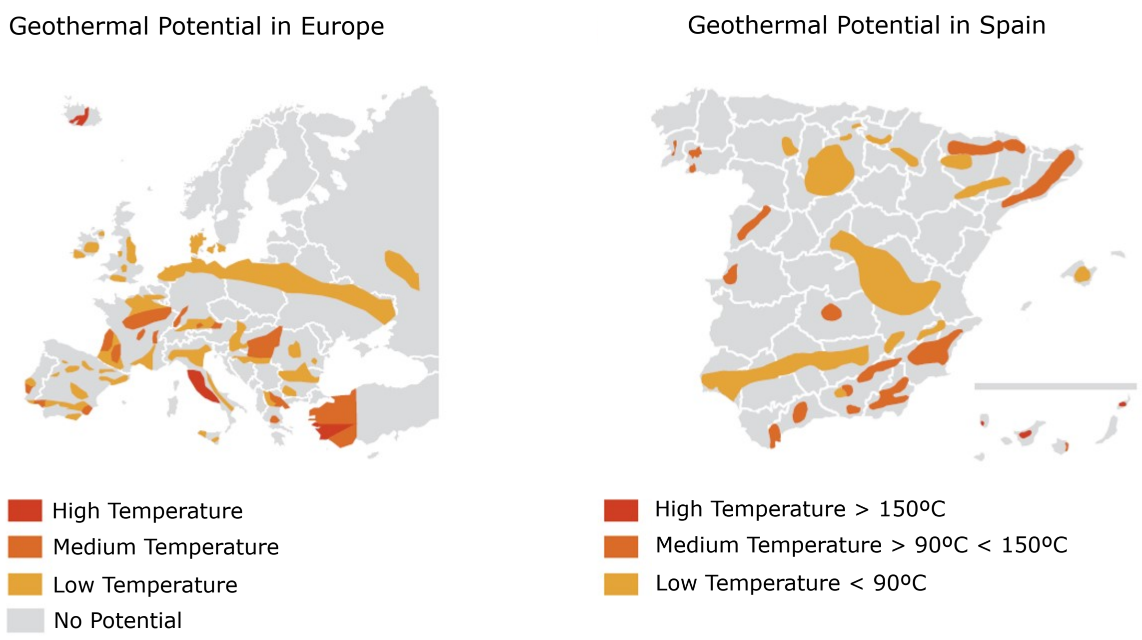


Figure 4.29. Suitable geothermal locations in Europe and Spain. Source: EGEC (European Geothermal Energy Council)

- Volcanic studies
- Geological and structural mapping
- Geo-chemical and geo-physical studies

4.4.4. Geothermal Energy: Environmental Impact

Are there any environmental impacts associated with geothermal power plants? The answer is YES. CO2 or other GHG emissions are low and, in any case, much lower than those generated in fossil fuel power plants. However, low concentrations of Radon may appear as a by-product of Uranium, one of the isotopes responsible for the heat accumulated below the Earth's surface. Radon is the second cause of lung cancer. All in all, this problem has few consequences, as geothermal plants include recycling procedures to avoid the emission of these particles.

4.5. Biomass

Bio-Energy can be defined as the energy that comes from materials derived from biological sources. Biomass can be understood as the organic matter that has been able to transform solar radiation into chemical energy. Within biomass energy, there are certain categories depending on the use. **Traditional biomass**, for example, is used (mostly in developing countries) for heating and cooking. It implies the burning of wood or similar biomass resources at homes and, consequently, it might be unsafe (and even unsustainable).

Modern biomass also includes the use of **biomass boilers in homes or buildings**. They use the so-called "pellets", which are small cylinders of compressed sawdust, as fuel.

Figure 4.30. Scheme of a domestic biomass boiler. Source: `http://bit.ly/2Gjping`.

Important! 5.1: Biomass Boilers: Examples

As an example, a 22 KW pellet boiler can be used for a 250 m^2 home, at an estimated cost of 16000 euros. For a building with 48 apartments, two 450 KW boilers would be necessary.

Biomass power plants use the same principle to generate electricity. Biomass has often been classified as renewable energy, for example by the European Union, because plant stocks can be replaced with new growth. However, it should be considered that this is an emitting technology, with CO2 release.

Important! 5.2: Biomass Plants

The largest biomass plant is located in Drax (North Yorkshire, UK), where 6 million pellets are used per year to supply 3 generators (600 MW)[a]. It is worth noting that the biomass material used in this plant comes mainly from the USA and Canada, what has led to some controversy[b].

[a] `http://bit.ly/2DAKpj0`
[b] `http://bit.ly/1qZxm3j`

Biomass power plants do not only generate GHG emissions, but also **PM (Particulate Matter) particles** that are also present in car emissions. PM is a complex mixture of extremely small particles and liquid droplets that get into the air. Once inhaled, these particles can affect the heart and lungs and cause **serious health effects**. There are some research groups working on the real-time detection of PM, for example the following one carried out by Ceder/Ciemat: `http://bit.ly/2revnvr`.

Question 5.1: Biomass

Read this article: `http://bit.ly/1qZxm3j`. Give your opinion on Biomass, providing any additional relevant data of your choice.

Question 5.2: Technological Brainstorming

Several RE technologies have been presented in this chapter: hydro-power, ocean (tidal, wave and OTEC), geothermal and biomass energies. Taking into account all the information provided during the course, try to imagine **a NEW renewable technology**. Briefly explain its working principle.

4.6. Conclusions

This course has placed a special emphasis on RE fundamentals, as well as on solar PV and wind energies. However, basic information has also been provided on hydro-power, ocean, geothermal and biomass energies, in order to give a more complete picture of the renewable energy scenario.

List of Figures