ENERGY AND TELECOMMUNICATIONS

Lecture Notes

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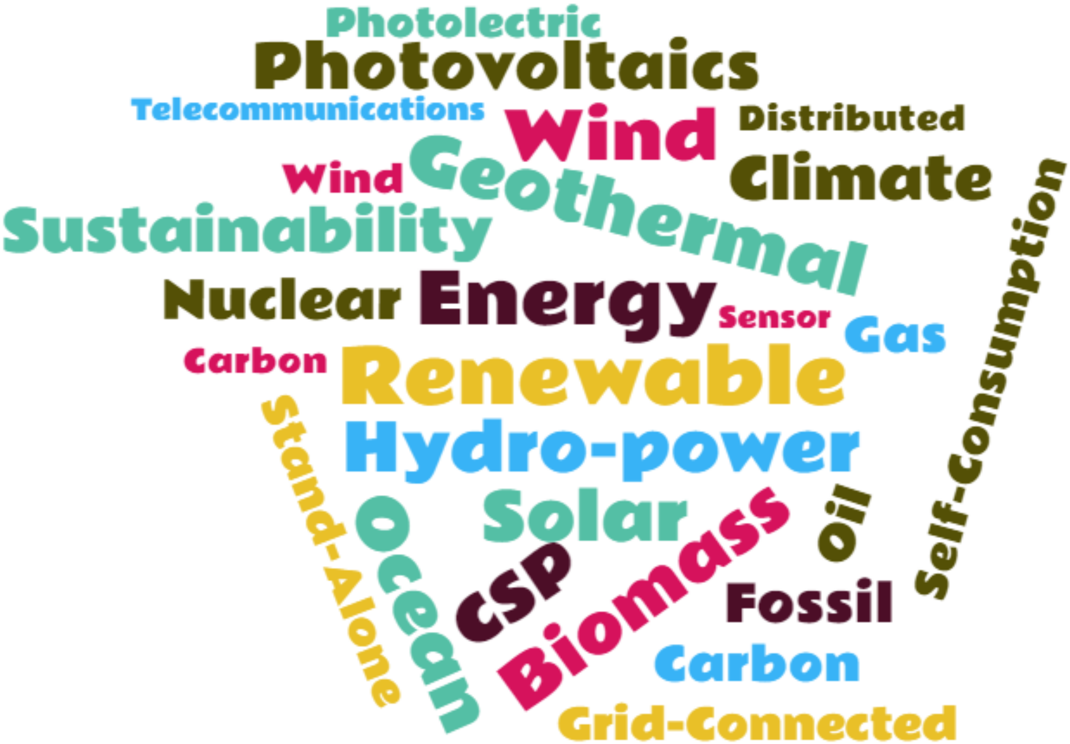
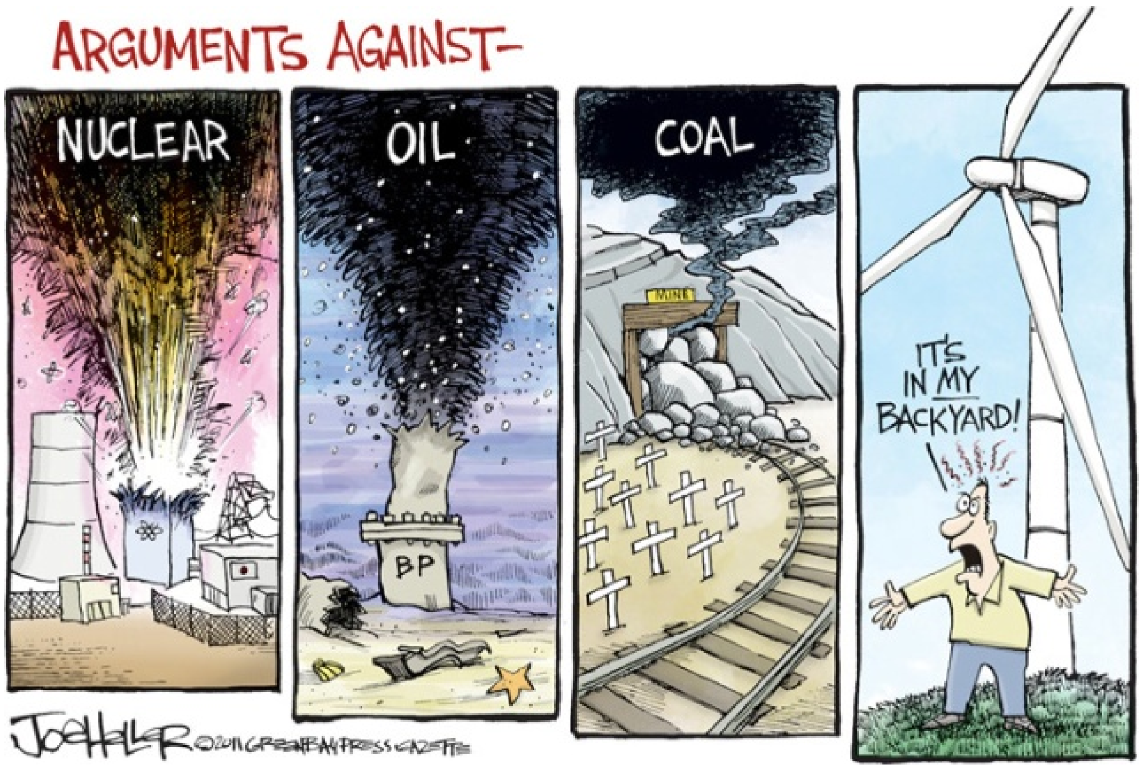


Solving the clean energy problem is an essential part of building a better world. We won't be able to make meaningful progress on other challenges – like educating or connecting the world – without secure energy and a stable climate. Yet progress towards a sustainable energy system is too slow, and the current system doesn't encourage the kind of innovation that will get us there faster.

Mark Zuckerberg, on joining Bill Gates to launch the *Breakthrough Energy Coalition* to invest in new clean energy technologies (November 30, 2015)



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Energy and Telecommunications

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Energy and Telecommunications: Renewable Energies

Abstract

An introduction to the main concepts of Renewable Energies (REs) will be provided in the initial section of the course. We will begin with a summary of the key elements that have given rise to the development of these technologies, including an analysis of the current national, European and worldwide situation. A special focus will be placed on the close relationship that exists between REs and Telecommunications.

If this "formal" presentation does not suit you, let's rephrase it! We will talk about the depletion of fossils fuels (and the dramatic change that this might imply to our society), about the climate change and Donald Trump, of wind turbines blowing out in failed tests ... and so on!

Although we will also consider and mention the "other" REs, such us ocean power, geothermal or hydropower technologies, the main focus will be on solar (both thermal and mainly photovoltaics (PV)) and wind energy.

The main goals of this course are:

- To become familiar with the main concepts related to renewable energies, such as climate change, sustainable development, decarbonization, capacity factor, energy storage in the electrical grid[1], distributed generation, etc.
- To discover the current situation of REs in Spain, Europe and worldwide.
- To understand the relationship between REs and telecommunications

[1] Also known as power grid or, simply, the grid

Energy and Telecommunications: Renewable Energies

Course Structure

This course has been divided into 4 chapters covering 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 of this chapter is for students to become familiar with the basics of REs. This includes understanding the reasons why these technologies came about, with a special focus on climate change. Basic information is also provided on the current situation in terms of renewable energies around the world and, obviously, in our country: Spain. Which is the leading country Photovoltaics or wind energy? How has the situation in China evolved over the last decade? What is Spain's current situation 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) and also about CSP (Concentrating Solar Power), where the sun's energy 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.

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Acronyms

BTS	Base Transceiver Station
CAES	Compressed Air Energy Storage
CSP	Concentrating Solar Power
E	Energy
EU	European Union
GH	Green-house
GHG	Green-house Gas
IDAE	Instituto para la Diversificación y Ahorro de la Energía [The Institute for the Diversification and Saving of Energy]
IPCC	Intergovernmental Panel on Climate Change
IR	Infrared
LCOE	Levelized Cost of Energy
PV	Photovoltaics
RE	Renewable Energy
REE	Red Eléctrica Española [Operator of the Spanish Electricity Grid]
SHM	Structural Health Monitoring
TFC	Total Final Consumption
TPES	Total Primary Energy Supply
UV	Ultraviolet

Units

°C	Celsius (temperature)
J	Joule (energy)
K	Kelvin (temperature)
Mtoe	Million Tonnes of Oil Equivalent
ppm	Parts per million
ppb	Parts per billion
ppt	Parts per trillion
Wh	Watt-hour (energy)
W	Watt (power)(capacity)

Glossary

Biomass is an industrial term for obtaining energy by burning wood, and other organic matter. Burning biomass releases carbon emissions, but has been classed as a renewable energy source in the EU and UN legal frameworks, because plant stocks can be replaced with new growth. As an energy source, biomass can either be used directly via combustion to produce heat, or indirectly after converting it to various forms of biofuel.

Concentrating solar power (also called concentrated solar thermal, and CSP) systems generate solar power by using mirrors or lenses to concentrate a large area of sunlight, or solar thermal energy, onto a small area. Electricity is generated when the concentrated light is converted to heat, which drives a heat engine (usually a steam turbine) connected to an electrical power generator.

Dynamic calibration (of power lines) refers to the possibility of transmitting a higher current than the one associated with the nominal ampacity of the line by measuring weather parameters such as sun radiation and wind speed and estimating their cooling effect upon the line.

End-Use Energy is the energy directly consumed by the user, like electricity, gasoline or natural gas.

Feed-in solar PV installation operates as a power plant, generating energy and injecting it into the power grid for its distribution.

Fossil fuel is a fuel formed by natural processes, such as anaerobic decomposition of buried dead organisms, containing energy originating in ancient photosynthesis. Examples of fossil fuels are oil, carbon and natural gas.

Greenhouse gas is an atmospheric gas able to trap or reflect heat (infrared radiation). Example of green-house gases are CO2 or methane.

Grid Parity occurs when an alternative energy source can generate power at a levelized cost of energy (LCOE) that is less than or equal to the price of purchasing power from the electricity grid. The term is most commonly used when discussing renewable energy sources, notably solar power and wind power

Hydro Power refers to the power derived from the energy of falling water or fast running water.

Levelized Cost of Energy is a parameter that allows making a direct comparison between different energy technologies, as it measures the lifetime costs of a given power plant (cost of building, operation, etc.) divided by the energy production. Its units are $\$/Wh$.

Photoelectric effect is the emission of electrons or other free carriers when light shines on a material.

Primary Energy is the energy that is directly harvested from natural resources.

Pumped-Hydro Power is based on the transportation of water to a higher reservoir, where that potential energy can be recovered by letting the water run to the base reservoir and activating a turbine located between both sites.

Renewable Energy is the energy obtained from the continuous or repetitive currents of energy recurring in the natural environment.

Self-consumption solar PV installation designed to provide energy to the building/system where it is located, for example a single-family home.

Solar PV Energy is based on the conversion of sun radiation (photons) to electricity (electrons) by means of the photoelectric effect.

Sustainable Development Development which meets the needs of current generations without compromising the ability of future generations to meet their own needs.

Sustainable Energy is the energy that does not significantly decrease with a continuous use, does not imply significant contaminant emissions or other environmental risks and does not imply the perpetuation of health risks or social injustices.

Chapter 1
Introduction

1.1. Energy: Primary and End-Use

This first chapter of the course will serve as an introduction to renewable energies in general and to the main concepts concerning this area. We are all familiar with the concept of energy, but it might be a good idea to remind ourselves:

According to the RAE[1], Energy can be defined as:

"the capacity of doing work. It is measured in joules. (Symb. E)."

Although we are accustomed to using electricity, it would be an error to associate energy only with this "type" of energy. If we take the examples of Solar PV energy or wind energy, it is true that there is a direct conversion to electricity. However, in solar thermal installations, the energy of the Sun is converted to heat. In addition, fossil fuels also generate energy, but electricity is not necessarily involved. This leads us to the key concept of **primary energy**:

Primary Energy is the energy that's harvested directly from natural resources[2]. **Fuels** and **flows** are the two sources or primary energy. Examples of the former are oil, carbon or natural gas; while the latter refers to energy flows such as wind, solar radiation or water flow, associated with wind and solar power and hydroelectricity, respectively.

Almost all the world's primary energy comes from fuels, as can be observed in Figure 1.1[3], where "Other" refers to geothermal, solar, wind, thermal, etc. This fact has serious implications, as fuels are normally associated with **emissions (e.g. CO2) and pollution**, although both fuels and flows can be **sustainable**. However, only flows can be **renewable**. We will explain these concepts later on.

All the sources of primary energy of a country (or region) are aggregated into a quantity called **total primary energy supply** (TPES). These sources normally require a conversion process before

[1] RAE: Real Academia Española [Royal Spanish Academy of Language]

[2] Source: `http://energyeducation.ca/encyclopedia/Primary_energy`

[3] Energy is expressed in this figure in Mtoe (Million Tonnes of Oil Equivalent, where 1 toe is the energy released by the burning one tonne of crude oil (1 toe = 11.63 megawatt-hour (MWh))).

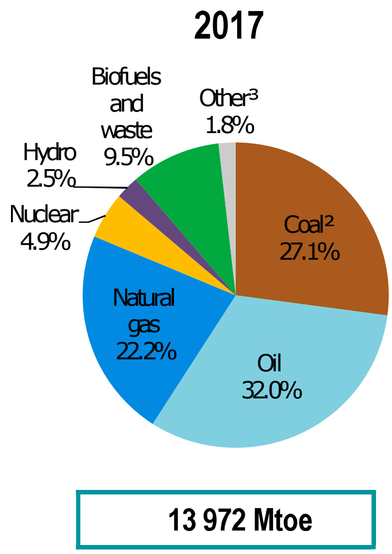

Figure 1.1. 2017 fuel shares of global TPES (Total Primary Energy Supply). Source: Key world energy statistics 2019. `http://bit.ly/361m2nW`

they can be used. For example, an oil refinery is needed to convert **crude oil** into a secondary fuel like gasoline, diesel or kerosene. **Coal** is usually put into a coal-fired power plant to generate electricity; or **wind** is harnessed by a wind turbine to also generate electricity.

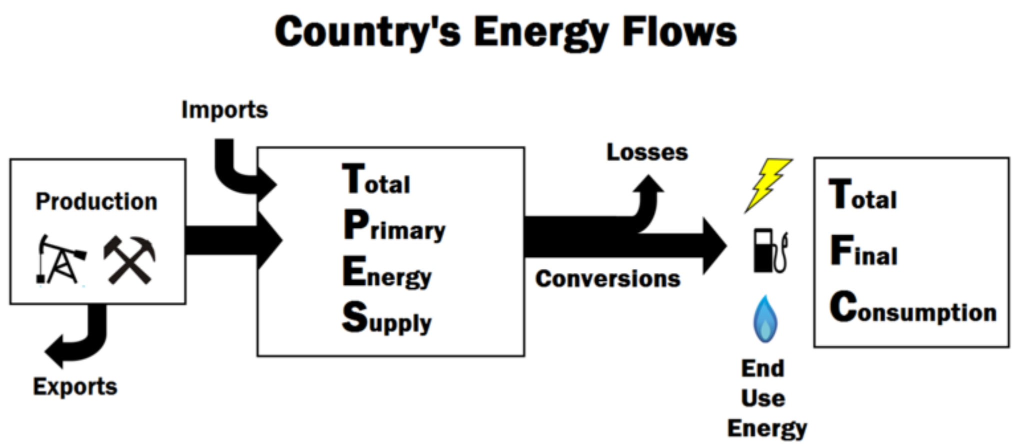

Figure 1.2. Schematic representation of the flow of energy in a country: from primary energy to end-use energy. Source: Energy Education. License: CC-by-SA 3.0. `http://bit.ly/2B0Bh66`

Looking at Figure 1.2, it seems that we should also define **end-use energy**.

End-Use Energy is the energy directly consumed by the user, like electricity, gasoline or natural gas. Looking at Figure 1.2, the **total final consumption** (TFC) of a country takes into account the complete profile of end-use energy.

A good example for illustrating the difference between primary energy and end-use energy is electricity. Primary energy is the energy used to generate electricity, while end-use energy is the amount of electricity that we use. Assuming a typical power plant efficiency of about 33 %, this implies that three times more fuel (e.g. carbon) will be used to generate electricity.

Important! 1.1: Primary energy and electricity

In this course, it is **extremely important** to correctly **differentiate between primary energy and electricity**, especially when talking about renewable energies. For example, in Spain renewable energies contribute to $\approx 40\,\%$ of the electricity generation, but only to $\approx 14\%$ of the TPES.

Question 1.1: Primary energy and electricity: Global

A challenge! Would you be able to find how much primary energy is used (globally) to generate electricity? Indicate this figure in % of global TPES.

1.2. Energy: Renewable and Sustainable

Renewable and Sustainable Energy are terms commonly used nowadays, but they refer to different types of energy. In addition, it is also important to clearly define both concepts to avoid any misunderstanding.

Possible definitions of renewable energy might be:

Energy obtained from the continuous or repetitive currents of energy recurring in the natural environment (Twidell and Weir, 1986)

Energy flows which are replenished at the same rate as they are "used" (Sorensen, 2000)

These definitions are perfectly valid, although they could be completed including a subtle addition:

Renewable Energy/*Green Energy* : Energy obtained from continuous and repetitive currents that can be harvested in our environment

Non-renewable Energy/*Brown Energy* : Energy obtained from static energy storages that are initially "hidden"

In these last definition a new concept appears: renewable energy sources are at hand, they can be harvested in our environment (e.g. solar radiation or wind flow). On the contrary, non-renewable energy sources need human action in order to be collected, for example drilling a well to extract oil.

Now that we have defined REs, it should be clear to us that the power plant shown in Figure 1.3 is associated with a **non-renewable energy source**.

But, wait a minute! Are you sure? Have you read the image caption? It seems that we are talking about geothermal power and ... it's renewable! In fact, this kind of energy is one of the key elements that make Iceland almost 100 % renewable. We'll talk about this a little bit later in the course.

Figure 1.3. Vapour emitted by the geothermal power plant in Nesjavellir (Iceland). License: Public Domain (Gretar Ivarsson). `https://bit.ly/2S2NQcL`

It is important to notice that a renewable energy is not necessarily a non-emitting energy (although in Figure 1.3 we are only looking at vapour, other renewable technologies such as biomass power do emit greenhouse gasses, such as CO_2).

It is now time to introduce the concept of "**sustainable energy**", that can be understood as the kind of energy that:

- Does not significantly decrease with a continuous use
- Does not imply significant contaminant emissions or other environmental risks
- Does not imply the perpetuation of health risks or social injustices

We can see that new concepts appear, which not are necessarily associated with REs.

1.3. Renewable Energy Technologies

Wind and solar power (mainly photovoltaics) are familiar renewable technologies. However, there are several other alternatives that can be even more relevant in some countries, such us hydropower or geothermal energy.

To analyze these technologies, we will use the classification made by the IDAE (Instituto para la Diversificación y Ahorro de la Energía), the Spanish institution responsible for everything related to renewable energies in our country. The specific goal of IDAE is:

"to support those technologies aimed at the decarbonization of the power (electricity) generation"

What is **decarbonization**? This refers to avoiding the use of, not only carbon, but all fossil fuels (carbon, oil and natural gas) as energy sources. It implies the implementation of REs in an attempt to reduce greenhouse (GH) emissions[1].

The IDAE establishes the shares of renewable energies in electricity production or final energy consumption, taking into account European directives. Currently (2010-2020 Plan), the IDAE considers the following renewable technologies:

- Wind Power
- Thermal Solar Power
- CSP (Concentrating Solar Power)[2]
- Photovoltaics (PV) or Solar Photovoltaics
- Biomass
- Bio-fuels
- Geothermal power
- Hydropower
- Ocean/Marine Power

Although they won't be analyzed in this course, it might be interesting to briefly comment on some of the more common non-renewable power stations (see Figure 1.4).

A conventional thermal power station uses fuels such as carbon, oil, natural gas or different combinations to generate electricity by means of a thermodynamic cycle (steam turbine).

A nuclear power station generates electricity using uranium as fuel by means of the nuclear fission process[3]. In nuclear fission, a "heavy" atom is split into lighter atoms, liberating a huge amount of energy in the process. In this way, heat is generated and used in a conventional thermodynamic cycle.

In a combined cycle power station electricity is produced by the conversion of the thermal energy of the fuel using two thermodynamic cycles: one corresponding to a gas turbine (normally using natural gas) and the other associated with a conventional steam turbine.

In a co-generation power station both electricity and thermal energy are simultaneously obtained. An advantage of this technology lies in its improved efficiency, given that the heat, which it is normally discarded in other situations, is used in this case, for example for district heating.

Question 3.1: District Heating

What is **district heating**? Look for information about this concept, explain it **in your own words** and mention at least 1 example.

[1] We will deal with this topic later on in the course.

[2] In Spanish, this technology is usually referred to as "Energía Solar Termoeléctrica"

[3] It is important to distinguish between nuclear fission and fusion. The latter is the process responsible for the generation of energy in the stars.

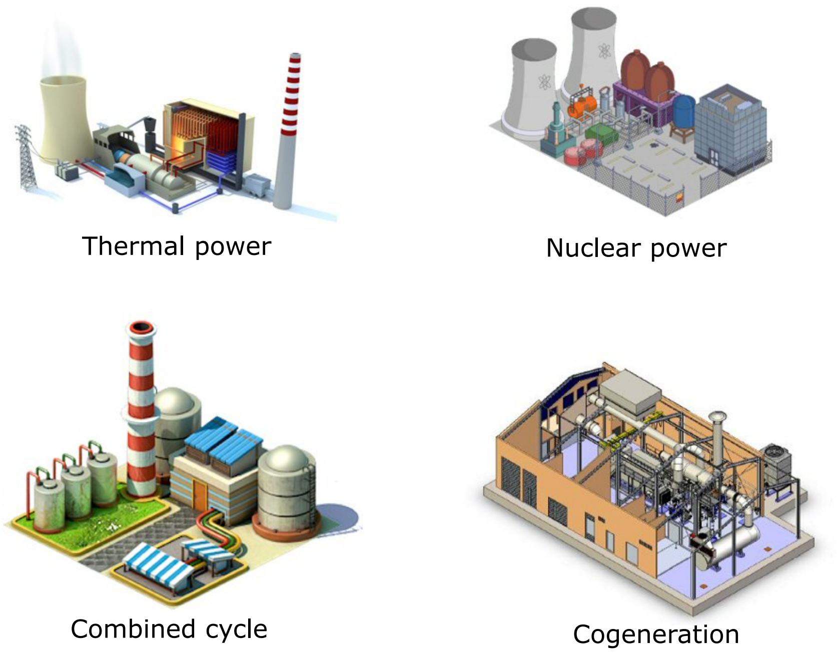

Figure 1.4. Conventional Non-renewable power stations.

1.4. Installed Power vs. Total Consumption (Electricity)

Although we will analyze the situation of REs in Spain in more detail in future sections, this is a good moment to introduce some key data about electricity generation in our country. In Figure 1.5, the **installed capacity (power) (on December 31, 2018)** for electricity generation has been represented for each technology, both renewable and non-renewable. It shows that **combined cycle (24.9 %)** is in first place, followed by **wind (23.4 %)** and **hydro power (17.3 %)**.

If we now look at Figure 1.6, it appears to contradict the previous data, as even if co-generation appears in the first place (21.9 %), nuclear follows in second place (21.2 %) and wind in third (20.6 %) for the **contribution of each technology to the total electricity demand in Spain in 2019**: What is happening? The answer is easy, and lies in the very **definitions** of **power** and **energy**.

Important! 4.1: Power and Energy

It is very important to clearly understand the difference between power (installed power in this case) and energy (energy generated by each technology to satisfy the total demand of electricity).

The installed power (also known as nominal power) refers to the total capacity of a given station to generate electricity. However, this capacity is not necessarily used all the time. For example, it is difficult to regulate and/or to stop the generation of nuclear power (this is why these power stations are continuously generating, and therefore it is the first one in the generation mix in Spain, in spite of its (relatively) low installed power), while wind power, on the contrary, is very easily monitored and controlled.

Other factors, such as the environmental contamination of specific technologies, may also influence their final contribution to the generation mix.

Important! 4.2: Installed capacity in Spain (2019)

The data shown in the autoref fig: 5 refer to the power installed in 2018, since at the time of writing these notes (January 12, 2020), REE (Red Eléctrica Española) has not yet published the definitive data referring to 2019. However, the installed power data (but not the generation data) vary little from year to year. In 2019 we know that 5,000 new MW of renewable generation have been installed (which implies a growth compared to the previous year of approximately 10%), **with a significant increase in solar PV** and, to a lesser extent, in energy wind.

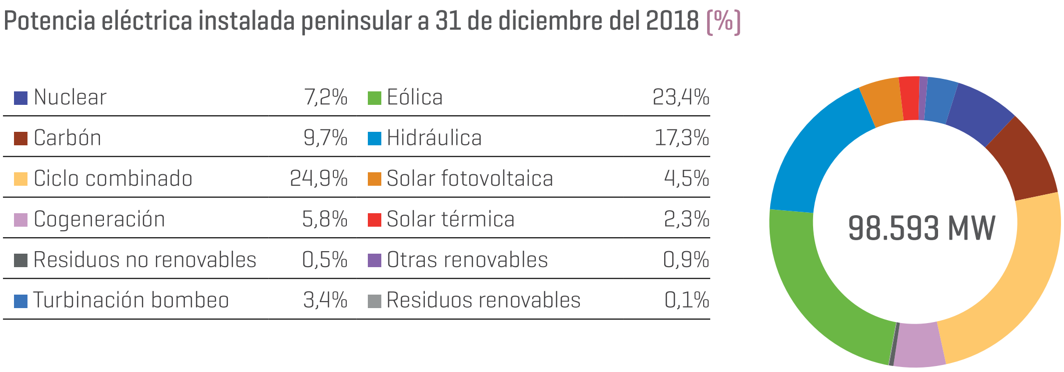

Figure 1.5. Installed capacity in Spain (2018). Source: "Informe del sistema eléctrico español (2018)" `http://bit.ly/2t9Kb2q`

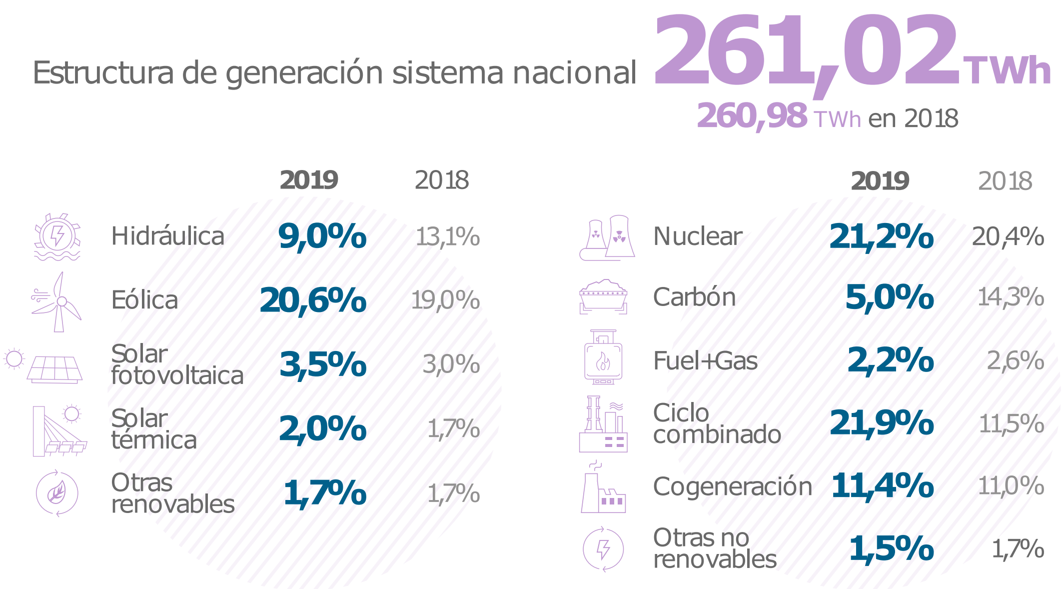

Figure 1.6. Electricity generation in Spain (2019). Source: "Previsión de cierre del sistema eléctrico español 2019" `http://bit.ly/2sJQPw7`

Within this context, it is interesting to look at typical powers associated with the different technologies:

Nuclear Power Station 1000MW

Combined Cycle Station 800MW

Coal-fired Thermal Power Station 500MW

Hydro-Power Station 100-400 MW

Wind farm 50MW[1]

Concentrating Solar Power (CSP) 50MW

Photovoltaic (PV) solar farm 20MW

Important! 4.3: Huge RE Plants

Apart from the conventional or average values, there are huge large-scale plants associated with different RE technologies:

The Crescent Dunes CSP plant has a nominal power of 110 MW: `http://bit.ly/1XN0Ixn`

In the UK there is a wind farm (off-shore[a]) project summing up a total of 1.2 GW: `http://bit.ly/2xwXpS0`

[a] Off-shore wind farms are built offshore (instead of on land), usually on the continental shelf, a few kilometers from the coast.

Question 4.1: Some hydro-power questions

Please answer the following questions in your OWN words:

- Can **hydro-power** be considered a **renewable** energy?
- Will the generation of a hydro-power station be **constant over the years**?
- What is a **pump**[a] hydro-power station?

[a] In Figure 1.5 it appears as "de bombeo"

1.5. What is the origin of Renewable Energies?

Nowadays, we are used to wind and solar energy, but we could still be using a pure carbon-based energy system today, covering all our energy demands. In this regard, it might prove interesting to briefly analyze the reasons behind the origins and outstanding development of renewable energies over recent years.

Although there might be other reasons, these are some important factors to take into account:

1. Fossil fuel depletion

[1] This might be the average power of a wind farm in Spain; however, there are large-scale wind farms with much higher powers.

2. Safety in energy supply
3. Climate change and sustainable development
4. Global energy demand increase

In the following sections, we will provide a short review of each factor:

1.5.1. Fossil fuel depletion

Is it true that fossil fuels will eventually run out? Without a doubt, this is a very controversial issue, but all the scientific studies are quite convincing: fossil fuel reserves are finite and they won't last forever. Considering the current rates of consumption, **coal reserves** might last for about **120 years**, **oil for 45** and **natural gas for 60**. These forecasts imply a "near" future without these energy sources.

Question 5.1: What do you think?

I would like to know your opinion on this matter: will we live in a world without oil (in the near future)?

To answer this question (in your **OWN words**), you can check some reliable blogs, articles or scientific papers (e.g. you might try GOOGLE SCHOLAR). We are looking for your opinion supported by credible data.

HINT: please note that it is important to know the author affiliation to better understand (filter) his/her opinions (i.e. it's not the same to be working for an oil company as for a public university).

There is an important issue associated with this matter. As can be observed in Figure 1.7, to keep up with the present rate of oil consumption, new more expensive wells will have to be exploited, thus increasing the associated oil cost[1].

Within this context, REs arise as a solution to covering the increasing energy demand and as a likely change of the energy model based on fossil fuels.

1.5.2. Energy dependency

As stated by the Eurostat:

*"**Energy dependency** shows the extent to which an economy relies upon imports in order to meet its energy needs. The indicator is calculated as net imports divided by the sum of gross inland energy consumption plus bunkers[2]"*

Spain is a good example of **energy dependency**: a huge amount of energy resources are imported from other countries (up to $\approx 80\,\%$), thus being exposed to geo-political situations that

[1] On the y-axis, **mbd** *stands for million barrels per day*.

[2] Here, **bunkers** refer to energy reserves (for example oil) that some countries may have, apart from consumption itself.

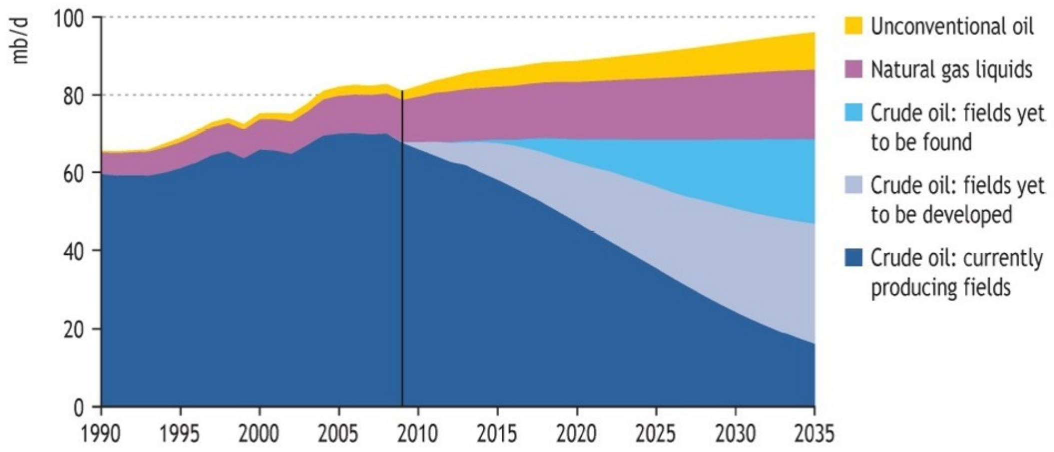

Figure 1.7. Forecast of oil production up to 2035. Source: International Energy Agency

may complicate these imports or increase the associated costs. Examples of these situations can be found in the recent crisis in the Middle East (Siria, Iraq, etc.) or the Russian-Ukrainian conflict affecting the supply of natural gas to many European countries.

Important! 5.1: Energy dependency in Spain

If we take into account the previous figure of ≈ 80% energy dependency and the fact that Spain does not have many fossil fuel reserves, it seems clear that a possible solution might lie in the exploitation of different RE Technologies as solar or wind power. In future sections we will analyze the regulation in our country and the actions that some governments have considered in this regard.

Question 5.2: Energy dependency in other Countries

To enable a comparison, it would be interesting to know the energy dependency in other countries from the European Union. Try to find these information, using a reliable source and choosing data as recent as possible.

1.5.3. Sustainable development

Apart from global energy demand, **sustainable development** is another key factor associated with RE development. A possible definition could be as follows:

"Development which meets the needs of current generations without compromising the ability of future generations to meet their own needs" (Brundtland, 1987)

Here is a similar definition by Eurostat:

*"**Sustainable development** is the organizing principle for meeting human development goals while at the same time sustaining the ability of natural systems to provide the natural resources and ecosystem services upon which the economy and society depend."*

This concept is directly related to climate change, which will be analyzed in a following section. At the same time, it is also related to REs, as they are an alternative to the use of fossil fuels. The latter exhibit several negative consequences, such as the depletion of natural resources, contamination, pollution and contribution to climate change.

Question 5.3: Sustainable Energy

The concept of sustainable energy was introduced at the beginning of this chapter. Find out the basics of **Biomass** Energy and answer the following questions:

1. Can **Biomass** be considered a **Renewable Energy**?
2. Can **Biomass** be considered a **Sustainable Energy**?

1.5.4. World Energy Consumption

Is there a relationship between REs and the global demand of energy? The answer is YES. Let's analyze Figure 1.8 and Figure 1.9, where the evolution of both **world energy consumption** and **world *per capita* energy consumption** have been plotted. A huge increase in the global demand can be observed in the former over recent decades. This effect might be explained by the rapid growth of the human population over the past one hundred years. However, Figure 1.9 also indicates that the energy demand *per capita* has also experienced a significant increase.

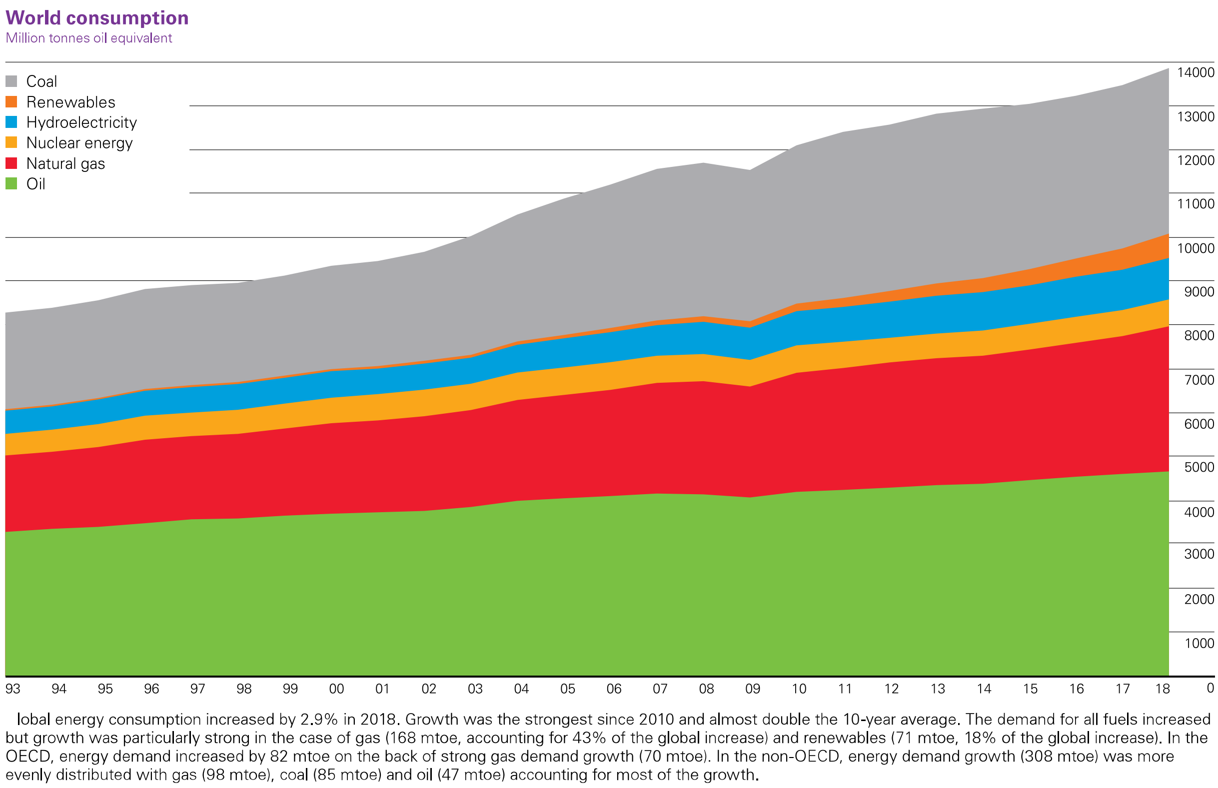

Figure 1.8. World consumption by source. Source: BP Statistical Review of World Energy 2019. `https://on.bp.com/2Fc07DG`

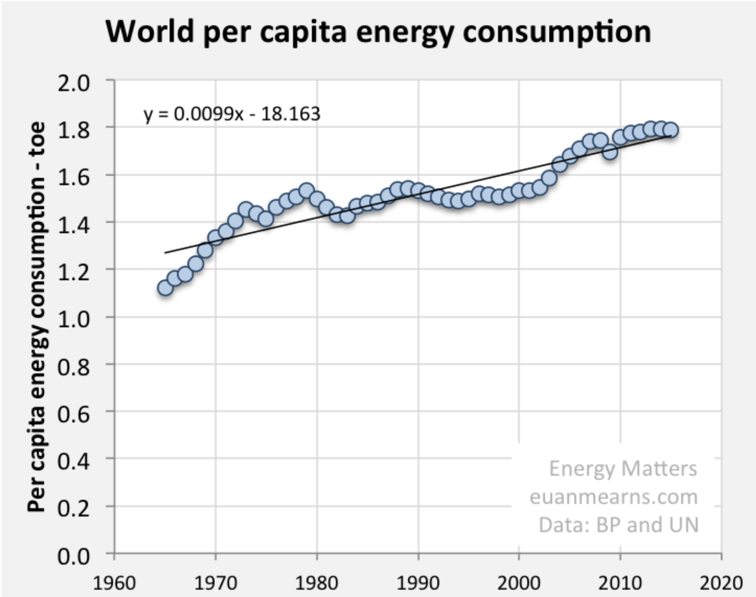

Figure 1.9. Global energy consumption per capita. Source: Energy Matters (enunmearns.com). `https://bit.ly/2R4o6Z6`

Important! 5.2: Primary energy vs. electricity

Although it has not been specified, it seems clear that the data in **??** concerns primary energy. Otherwise, it would have been specified that we are talking about electricity generation and/or consumption.

Figure 1.10 may prove useful to better understand this evolution in global energy demand. On the one hand, the global demand (primary energy) has doubled in 40 years. Even if the share of some sources like oil has decreased (from 46.2 to 31.3 %), all of them show an increase in their total contribution. In addition to oil's evolution, the increase in the shares of coal and natural gas is also significant, as is the growth of nuclear power.

If the analysis is now focused on global electricity generation, the resulting figure will present some differences (see Figure 1.11). For example, the contribution of oil has decreased significantly (from 24.8 to 4.1 %), while natural gas and nuclear power have increased accordingly. It is worth mentioning that in this case hydro power is a significant technology, covering 16 % of global electricity generation.

Important! 5.3: Cost of fussil fuels

Figure 1.11 can be better interpreted if the price associated with each energy source is known. The price of an oil barrel is $\approx$ 35$. Considering that 1 barrel generates 6.1GJ of energy, this results in **5.7$/GJ for oil**. The figures for **coal and natural gas** are **1.6 and 2.5$/GJ**, respectively.

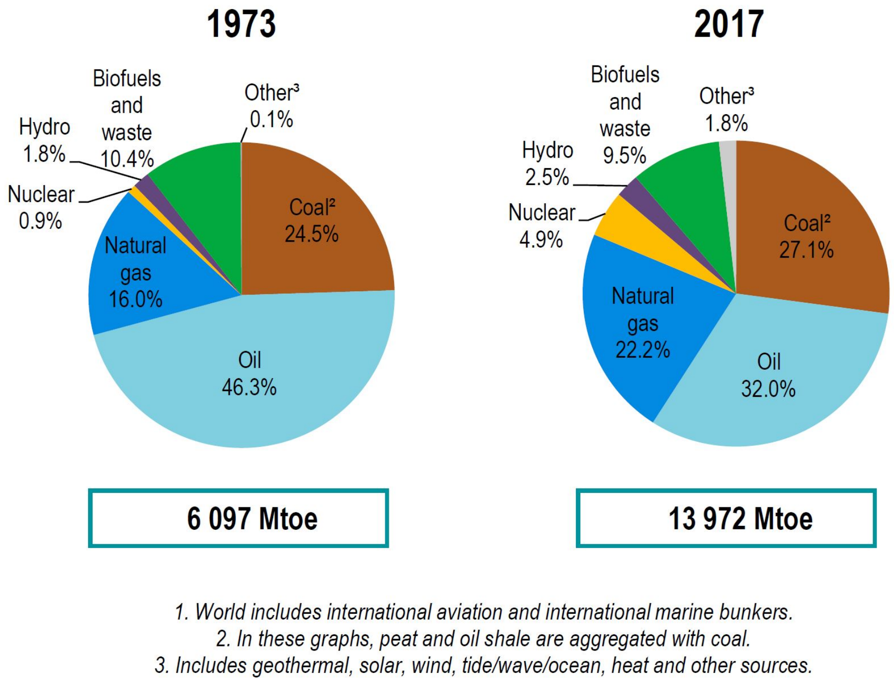

Figure 1.10. Evolution of the contribution of each energy source to the global primary energy supply. Source: Key world energy statistics 2019. `http://bit.ly/361m2nW`.

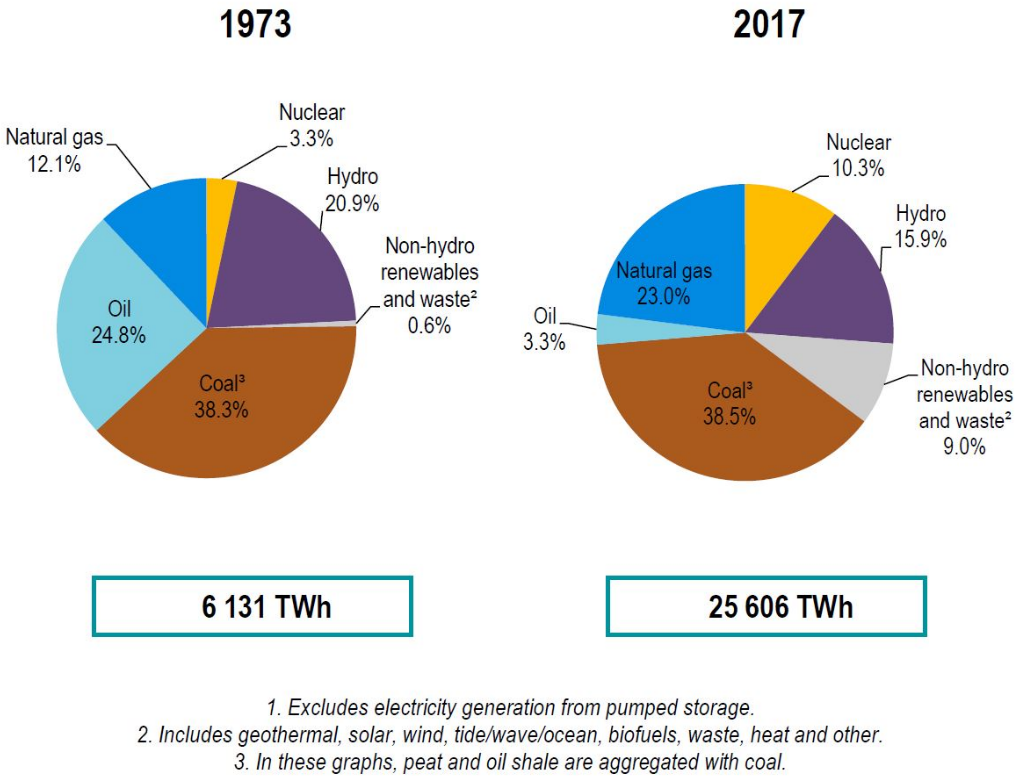

Figure 1.11. Evolution of the contribution of each energy source to the global electricity generation. Source: Key world energy statistics 2019. `http://bit.ly/361m2nW`.

Question 5.4: Primary energy supply by geographical region

When we are looking for data, it is extremely important to find the right sources. As regards energy issues, the Key World Energy Statistics (published by the IEA: International Energy Agency) is a very suitable source.

Before looking into this report, try to make a list ordering the consumption of primary energy by region (in America, Europe, Asia, Africa and Oceania). How would you order these regions in terms of their TPES?

Now look for this information in the 2019 report by the IEA and write a short comment on these data. Are you surprised by the region that appears in 1st position? Justify these results in your **OWN** words.

1.6. Climate Change

There is no doubt that **climate change** (also known as **global warming**) is one of the main reasons for RE development over recent decades. It is difficult to provide a brief summary on this topic, as there are many books, films[1] and courses[2] about it.

In the following pages we will provide a short introduction to the key elements concerning **climate change**.

1.6.1. Climate Change: Greenhouse Effect

The Greenhouse (GH) Effect explains the relationship between the incoming (and outgoing) radiation in the atmosphere, as well as the ability of some gases (Co2, water vapour, methane, etc.) to greatly influence these processes.

The **GH effect** is clearly explained in Figure 1.12, where incoming (red) and outgoing (blue) radiation have been represented. It can be observed how the wavelenghts associated with the incoming radiation from the Sun (ultaviolet - UV, visible, short IR) are clearly shorter than those related to the outgoing one (infrared - IR). Around 70 to 75% of the solar radiation goes through the atmosphere, mainly filtering the UV components. The outgoing radiation is generated by the heat of the Earth, as every "hot" object generates IR radiation.

Important! 6.1: Wien's Law

All hot objects emit radiation: Wien's law establishes a relationship between the temperature of the object and the wavelength of the emitted radiation. Figure 1.12 indicates that the radiation of the Sun is associated with a temperature of about 5500 K, while that of the Earth is approximately 258 K.

The total absorption and scattering spectrum, generated by the contribution of the different

[1] Like the famous documentary by former USA vice-president Al Gore *An Inconvenient Truth* or the recent movie by Leonardo di Caprio *Before the Flood*.

[2] For example *Climate Change: The Science*, to be found in the EdX platform: `http://courses.edx.org/courses/course-v1:UBCx+Climate1x+1T2016/info`

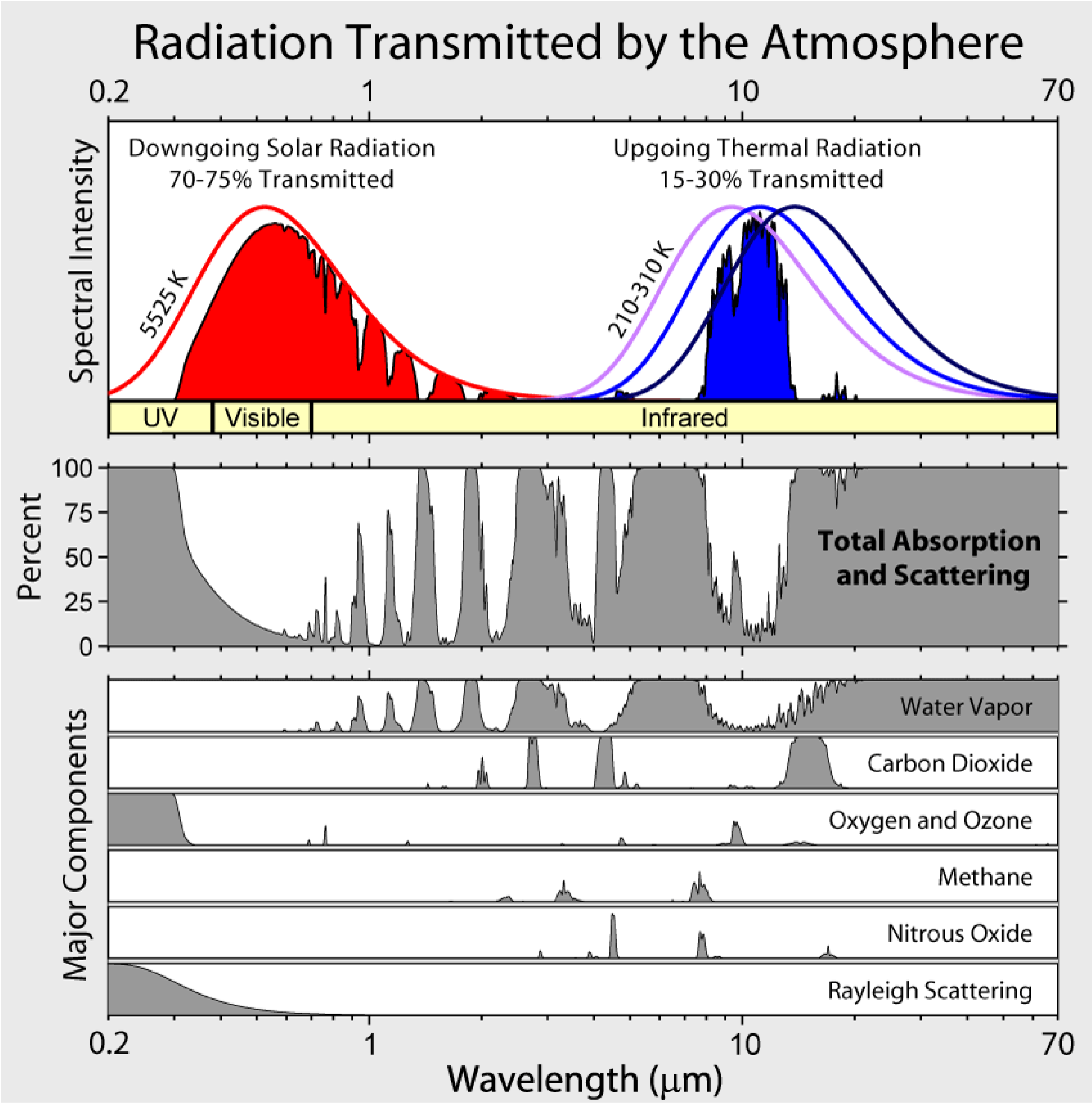

Figure 1.12. Radiation transmitted by the Earth's atmosphere (incoming (red) and outgoing (blue) radiation). Source: Wikimedia. License: CC-BY-SA 3.0. https://upload.wikimedia.org/wikipedia/commons/7/7c/Atmospheric_Transmission.png/

Greenhouse Gasses (GHGs) has been represented in the central part of the figure. Each individual spectrum (for CO2, water vapour, O2, ozone, methane and NOx (nitrogen oxides)) is shown at the bottom. Obviously, for increasing concentrations of GHGs, there will be an increase in their blocking effect of the outgoing radiation.

Important! 6.2: GH: the good, the bad or the ugly?

It is common to assume that the GH effect is bad for planet Earth and for all of us, however, this should probably be restricted to the climate change provoked by man (anthropogenic climate change): the increase in GHG emissions since the industrial revolution.

We have to consider that our planet would not be the same without the GH effect. The "correct" concentration of GHGs in the atmosphere allows the temperature on the Earth to be "suitable" for life. The problem comes with the excess of these GHGs.

Some scientists have calculated the contribution of the GH effect in **around 33 K**. However, this is a basic approximation and a very controversial topic. Prof. Robert G. Brown's (Duke University) article is very interesting in this regard: *Earth's baseline black-body model a damn hard problem* `https://bit.ly/2GZs84z`

1.6.2. Climate Change: Positive and Negative Feedbacks

The study of climate change is a **rather complex problem**, as it involves several different scientific areas. A good example of this complexity lies in the analysis of the feedbacks derived from various factors and that may have a positive or negative effect on climate change. Note that a positive feedback in this context implies an effect that makes the climate change stronger, while a negative feedback moderates its effects.

Positive feedbacks

Water vapour On the one hand, water vapour can be regarded as a positive feedback, given that an increase in GHG concentration in the atmosphere will imply higher temperatures and a higher water evaporation from the oceans, thus reinforcing the temperature increase. On the other hand, water vapour also contributes to the formation of low clouds that reflect part of the solar radiation, thus being a negative feedback. The former effect is normally considered as more important, while the second adds uncertainty and makes it complicated to develop reliable computer models.

High clouds If the water vapour generates high clouds, these block the outgoing infrared radiation (more than the incoming solar radiation), thus contributing to a temperature increase.

GHG release Several GHGs are trapped in different reservoirs like oceans or the Siberian tundra or permafrost. A global warming might imply a fast melting of the permafrost, which covers a million square kilometers, and thus a higher release of methane or CO2, again contributing to global warming.

Albedo effect The albedo or albedo effect (from the Latin albus (white light)) can be defined as the radiation reflected from a surface. Within this context, the Earth's albedo can be understood as the amount of reflected energy in terms of the incoming radiation (it will vary between 0 and 1). The mean value for the Earth's albedo is 0.367. As can be observed in Figure 1.13, ice has a higher reflectivity that other surfaces (rock, water, etc.), so its contribution to the global albedo will be higher. Considering climate change, global warming will imply a decrease in the total ice surface, thus contributing to an increase in the absorbed incoming radiation and, consequently, to a greater global warming.

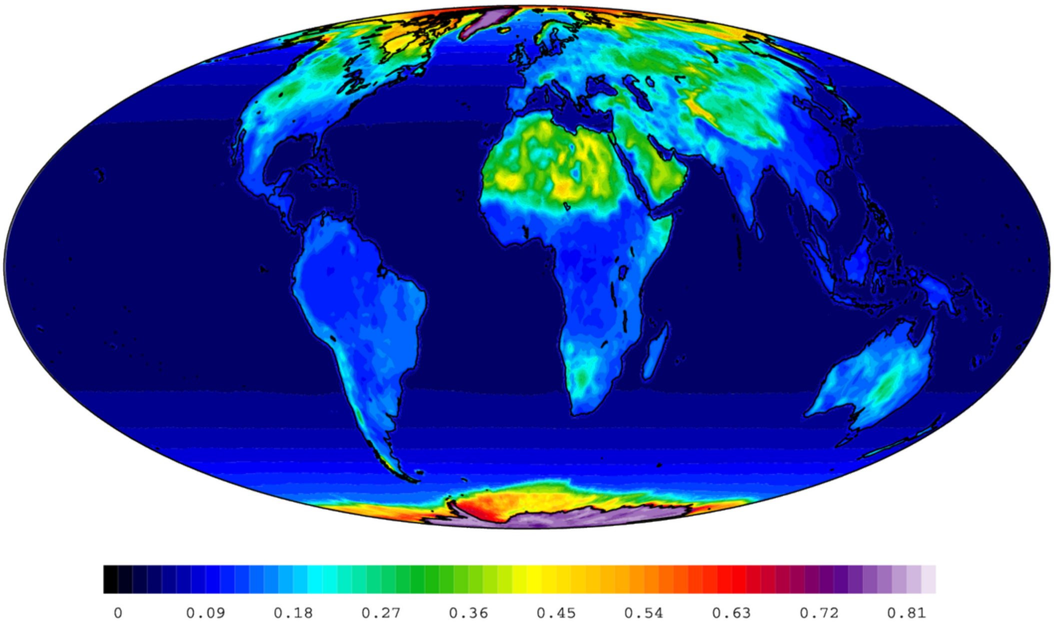

Figure 1.13. Average albedo in clear sky conditions. Source: `http://www-cave.larc.nasa.gov/cave/fsw-sfcalb/`

Deforestation Droughts, fires and desertification affect forests all around the planet. All these situations give rise to the release of huge amounts of CO2 (that are fixed to vegetation) into the atmosphere, thus contributing to the climate change.

Negative Feedbacks

Blackbody radiation As we already know, every hot object emits radiation. In this regard, the Earth can be modeled as a **blackbody** (an ideal material that absorbs all the incoming radiation and emits electromagnetic radiation depending on its temperature). The amount of radiated energy is given by $E = g{\cdot}T^4$. It seems clear that an increase in the temperature of the planet will also imply a higher emission of EM radiation, thus favoring a decrease in the temperature.

Low clouds As already mentioned in the water vapour section, an increase in the Earth's temperature will lead to a higher rate of low cloud development. As these formations reflect and absorb part of the visible spectrum of the solar radiation (between 400 and 700 nm), we are talking about a negative feedback.

Fertilizing effect A funny and mostly unknown fact about CO2 is that its presence in the atmosphere fosters the growth of plants, which will also contribute to a higher CO2 absorption and to lowering the global warming effect. Of course, this effect should be considered together with the other CO2 contributions to climate change.

CO2 spontaneous removal from the atmosphere There are several phenomena that can lead to a higher CO2 absorption by the oceans if its levels in the atmosphere increase. For instance, the chemical erosion of rocks or the formation of shells. However, these processes operate on huge time-scales, thus their influence on climate change is not clear.

1.6.3. Climate Change: Greenhouse Gases

The effect of GHGs in terms of the Climate Change has already been introduced in previous sections. Table 1.1 presents a very interesting comparison between the concentration of the main GHGs in our atmosphere today and in the pre-industrial age[1]. It can be observed how these 4 gases were already present in the atmosphere, but their concentration have significantly increased over time, not just due to the emissions derived from using fossil fuels, but also from the effects of other activities such as agriculture, animal farming and the subsequent deforestation.

The parameter ***radiative force*** that appears in Table 1.1 indicates the additional irradiance[2] derived from the greenhouse effect of these gases. CO2, for instance, contributes with an irradiance of $1.46W/m^2$, which has to be added to the sun irradiance, of $\approx 1000W/m^2$. As can be derived from Table 1.1, CO2 contributes by 75% to the overall global warming potential derived from GHGs.

GHG	Pre-industrial	Nowadays	Radiative Force (W/m^2)
CO2	280 ppm[3]	387 ppm	1.46
Methane	700 ppb	1745 ppb	0.48
NO2	270 ppb	314ppm	0.15
CFC-12	0	533ppt	0.17

Table 1.1. Evolution of the concentration of Greenhouse Gases.

Figure 1.14 is very interesting, not only from a strictly scientific perspective, but also from a historical point of view. These data show the first measurements of CO2 levels and their correlation with climate change. The graph is often referred to as the Keeling curve, named after the scientist who began to take the measurements in 1960, Charles Keering. It is worth noting that, apart from the annual average (blue curve), seasonal variations have also been represented (red curve, detail in the inset on the upper left side). These variations are mainly due to photosynthesis.

1.6.4. Climate Change: Global Temperature Variation

There is a broad consensus within the global scientific community that the global warming (the increase in the temperature of the Earth (surface)) of the previous decades is directly related to the higher concentration of GHGs in the atmosphere. As can be observed in Figure 1.15, the temperature of our planet has risen by $0.6°C$ in the last 30 years, which would imply a $2°C$ increase by 2100.

But, why are these scientist so sure about the reasons that lie behind this phenomenon? Because their **models** support this hypothesis. As you probably know, computer models are used in a wide variety of fields to simulate different processes or scenarios. In this case, different causes have been taken into account, from the effect of sulfate aerosols to volcanic and solar activity. It seems clear (see Figure 1.15) that, according to these models, GHGs play a key role in this problem. There is other evidence to support this hypothesis: for example, a GHG-driven global warming implies a cooler stratosphere (in comparison to lower atmosphere layers).

[1] Before the beginning of the industrial revolution, i.e. before 1760, approximately.

[2] Irradiance can be defined as the power (radiant flux) received by a surface per unit area. In the context of this course, irradiance will be used as a synonym of solar irradiance.

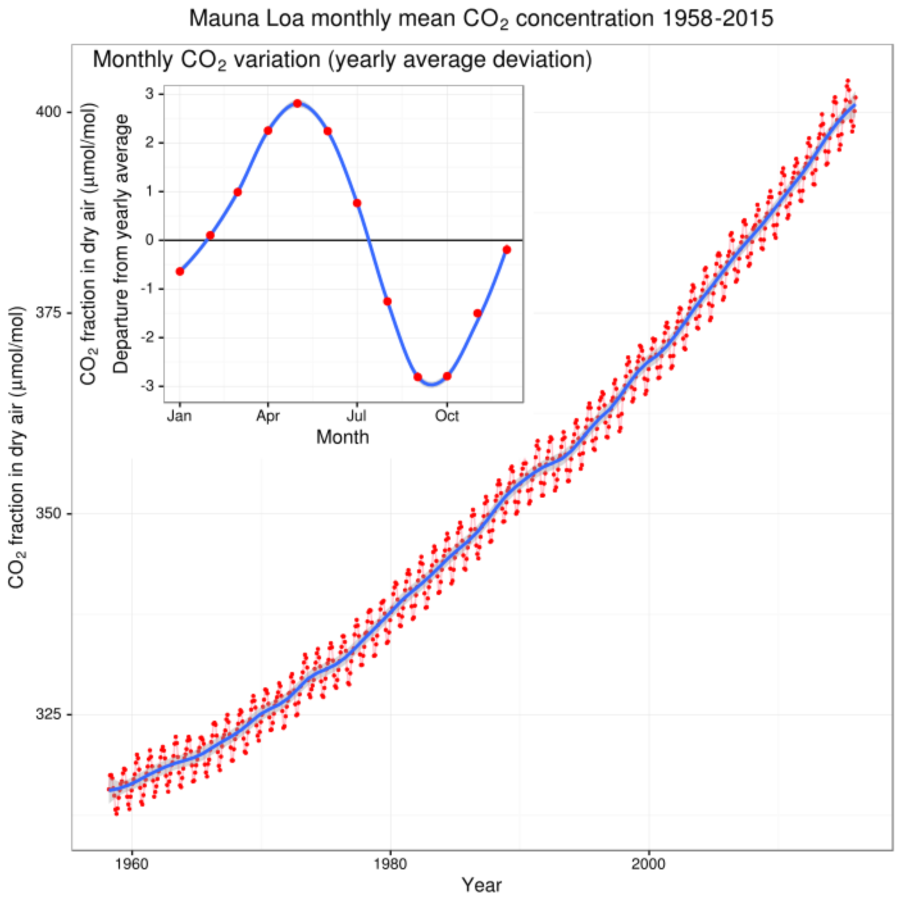

Figure 1.14. Evolution of the CO2 concentration in Mauna Loa island (Hawaii) (*Keeling Curve*). Source: *Delorme - Own work. Data from Dr. Pieter Tans, NOAA/ESRL and Dr. Ralph Keeling, Scripps Institution of Oceanography*. License: CC BY-SA 4.0. `http://bit.ly/2yZvyyM`

1.6.5. Climate Change: 21st Century Forecasts

By means of different actions, it seems clear that the effects and predictions of climate change have given rise to a (more or less) unanimous response from worldwide citizens, governments and institutions. However, the real outcomes of actions such as the **Paris Agreement**[1] are not clear, for example in terms of CO2 emission reductions. In this way, several research groups have developed their own prediction models to estimate the temperature at the end of this century. Figure 1.16 shows these projections, assuming that CO2 emissions won't be significantly reduced. As can be observed, the increase in the Earth's temperature might go up by 5° C[2].

1.6.6. Climate Change: Skeptics and Deniers

In recent years, positions on climate change have been highly polarized, with those accepting it as a reality and those who think that it is a mere invention. Studies performed in the USA

[1] To learn more about the Paris Agreement: `http://bit.ly/1Zw71oD`

[2] Predictions from different range estimate temperature increases from 2 to 5°: it seems clear that this is a very complex problem involving a huge amount of factors (and feedbacks).

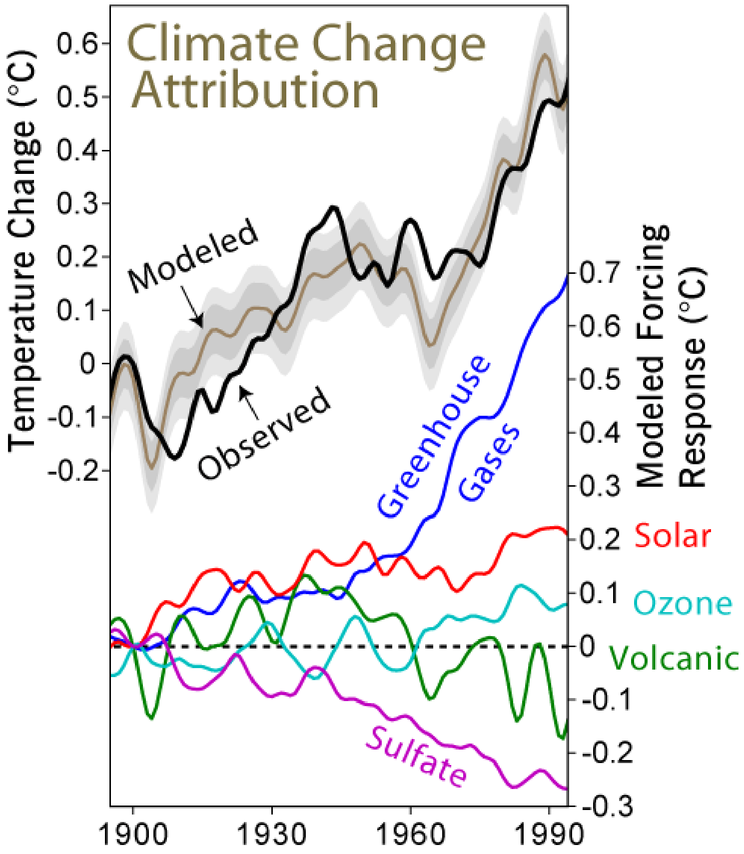

Figure 1.15. Evolution of the average temperature on Earth's surface. Source: NASA. License: CC BY-SA 3.0 `http://bit.ly/2BWnopk`

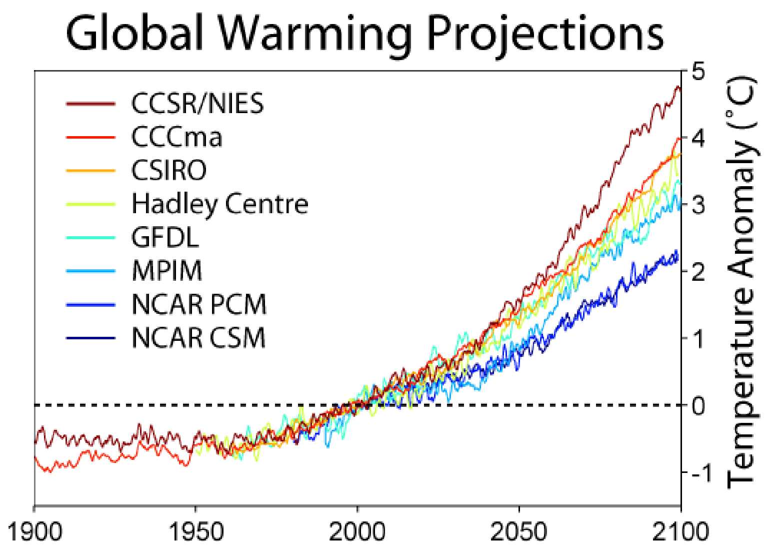

Figure 1.16. Evolution of the average temperature on Earth's surface according to different models. Source: NASA. License: CC BY-SA 3.0 `http://bit.ly/2BWnopk`

suggest the following citizen classification[1]: alarmed (12 %), concerned (27 %), cautious (25 %),

[1] *Renewable Energy: A first Course* by Robert Ehrlich.

disengaged (10%), doubtful (15%) and dismissive (10%). The number of people (in the USA) that exhibit a negative view of climate change is rather high (35% from disengaged to dismissive). It may prove interesting to analyze the arguments typically used by skeptics and deniers to dismiss climate change as a reality:

Urban heat island effect referred to the fact that many temperature measurements are taken via weather stations located in urban environments, where temperatures are supposed to be higher than in rural environments due to traffic, urbanization and so on. However, studies on scientific papers normally correct this effect, whose impact is supposedly very limited[1].

Satellite data show a cooling trend instead of a global warming. It seems that at the beginning of the climate change science, satellite data really showed a decreasing pattern in the temperature of the Earth. However, there were some corrections to be performed to the satellite instrumentation that were not considered initially, thus explaining this unexpected behaviour.

Temperatures decreased around mid-20th century, despite the increase in CO2 levels : as already shown in Figure 1.15, it is true that temperatures started to decrease by 1940 while CO2 concentration increased in the atmosphere. Scientists believe that this effect was caused by the contribution of sulfate aerosols, which constitute a negative feedback contributing to both cloud formation and *"global dimming"*, thus reducing the amount of radiation reaching the surface of the Earth. This is a good example of the huge complexity of the science that lies behind climate change, with several intertwined positive and negative feedbacks.

Computer models are not reliable: As already discused, it is obvious that there are differences between the results provided by the models considered (as illustrated in Figure 1.16) as also occurs with models associated with the weather forecast. However, all these models are based on known laws of Physics and have been validated via empirical observations and most of them have given rise to correct predictions, like the stratospheric cooling or the increase in temperature in the Arctic.

But, we aren't even able to predict next week's weather! Weather forecasting has little in common with long-term climate predictions. In the latter, the influence of short-term random variations disappears. A good example in this regard is the comparison between the prediction of the long-term demographic evolution of a country vs. the number of children being born in a given hospital in a week: this latter prediction will most likely involve a higher degree of error.

Climate change and global warming are part of a natural and periodic process of the Earth. It is widely accepted that there are several natural causes, such as variations in the sun's behaviour, which may provoke climate change, as it has happened before in the past. However, it would be extremely difficult to justify, from a scientific point of view, why the increase in GHG concentration in the atmosphere should not involve an increase in temperatures. It is worth noting that climate change studies, such as those developed by the IPCC (Intergovernmental Panel on Climate Change)[2], always include uncertainty factors in their predictions, indicating that exact forecasts can always be discussed. However, studies against climate change do not tend to consider these subtleties.

[1] If you want to go deep into this topic, you can check the following paper by Peterson et al.: *Assessment of Urban Versus Rural In Situ Surface Temperatures in the Contiguous United States: No Difference Found* `http://bit.ly/2BU4qA3`

[2] https://www.ipcc.ch/

CO2 levels in the atmosphere are the consequence (and not the result) of climate change. The Earth's rising temperatures implies an increase in CO2 levels due to the contributions of oceans and permafrost, for example. Although this is known to have happened on our planet in the past, there is also a huge amount of evidence that clearly indicates human contribution to the rising concentration of this GHG. It is also worth noting that, as already discussed, CO2 can act as both positive and negative feedback on climate change.

A warmer climate and higher CO2 levels would be beneficial: it is true that this might be the case for specific regions around the globe. However, taking into account climate change outcomes such as sea level rising, increase in the acidity of oceans and the occurrence of more extreme weather events (to mention just a few examples), it really does not seem that climate change would be any good for human beings or the Earth's ecosystems in general.

There is no global scientific consensus regarding climate change. This is one of the most common reasons for questioning the so-called anthropogenic climate change[1] when there is clear consensus on this issue, which is quite remarkable taking into account the vast amount of institutions and research areas involved. A good reference is the paper by Cook et al. in 2013[2], where 11944 scientific papers on the topic are analyzed and the estimated global consensus on the anthropogenic origin of climate change is 97.2 %.

Important! 6.3: Donald Trump and climate change

Donald Trump, USA President elected in the 2016 campaign, is a good example of climate change skepticism. During his campaign, he claimed several times that he would remove all the USA funds initially assigned to fighting climate change. In 2012 he tweeted the following message suggesting that the whole climate change issue was a Chinese invention:

"The concept of global warming was created by and for the Chinese in order to make U.S. manufacturing non-competitive"

1.6.7. Climate Change: Conclusions

Some basic matters concerning climate change have been covered in the previous sections, in order to provide information about a few key points on this very complicated and controversial topic. The reality of climate change and its human origin are facts widely accepted by the international scientific community. It also seems obvious that climate change implies serious challenges for human beings and ecosystems. For this reason, different organizations and governments have been involved for many years in the development of effective ways to control or mitigate this phenomenon. The Kyoto Protocol[3] or the recent Paris Agreement[4] are examples of actions aimed at controlling GHG emissions.

Renewable energies are a key factor in the transformation that the energy sector (and societies around the world) should undergo in order to pursue this fight against climate change. GHG emissions directly related with electricity and heat generation can be estimated to be around 25 % (of total GHG emissions).

An interesting study in this regard is presented in Figure 1.17, where GHG global emissions have been classified by source and sector. Emissions derived from fossil fuels amount to 65 %,

[1] Theory that concludes that the climate change that the Earth is currently experiencing is due to human activity

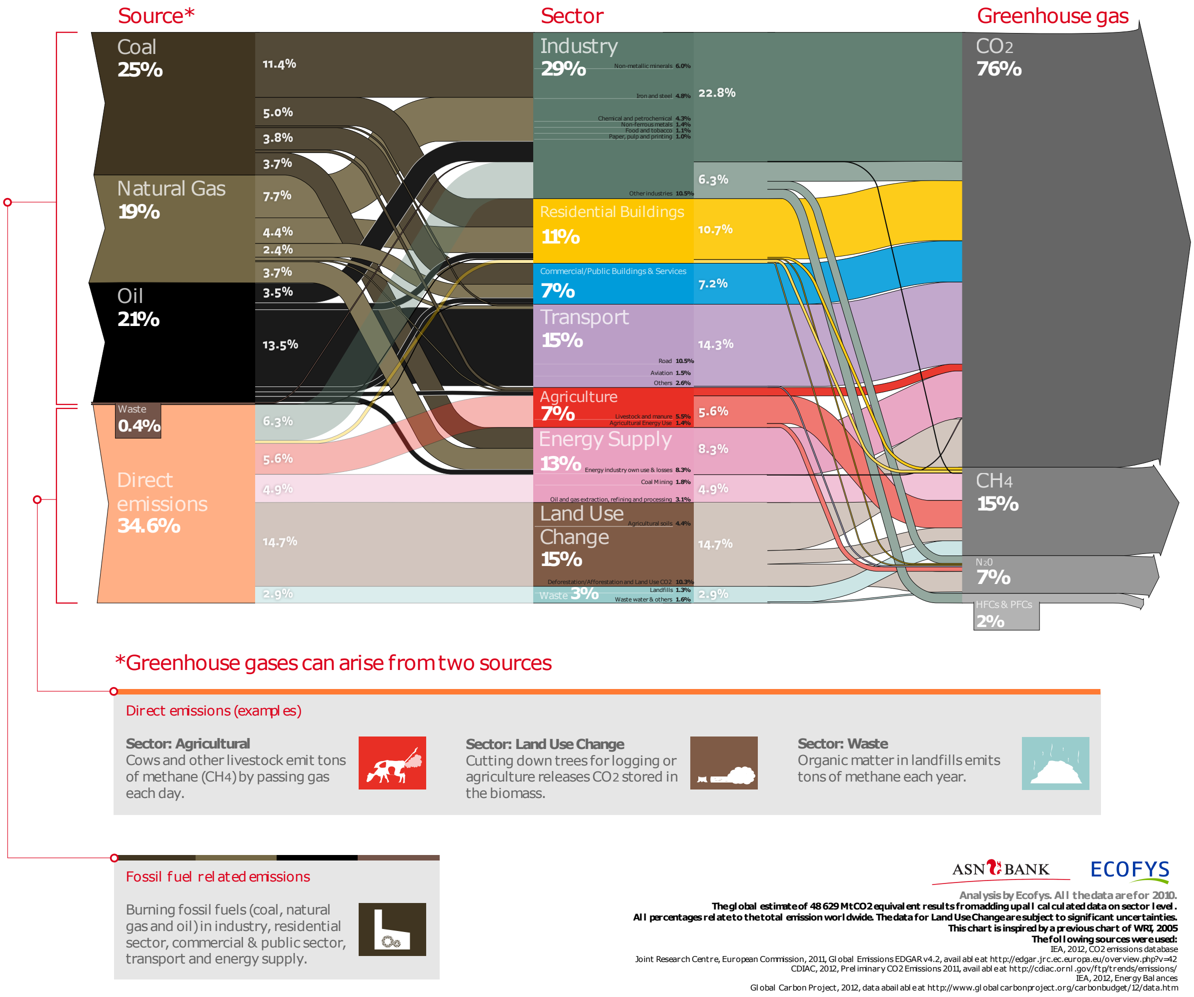

Figure 1.17. World GHG emissions flow chart. Source: ECOFYS. `http://bit.ly/2AwkICXk`

while the remaining 35 % is labelled as *"direct emissions"*. In the latter, emissions from agriculture and animal farming (methane emissions from cattle), deforestation or waste are considered. A higher quality version of this graph can be seen at `http://bit.ly/2AwkICXk`. Having analyzed Figure 1.17, it seems clear that REs will play a major role in the transformation that the energy sector will have to undergo in the coming years.

Another interesting strategy related to climate change is based not on reducing GHG emissions, but on directly **capturing these gases in the atmosphere, particularly CO2**. These solutions have to be designed, not only to capture CO2, but also to transform and/or store it conveniently, for example in exhausted oil wells. Several factors, from public funding to the potential risks of these CO2 reserves, will determine the success of these proposals.

The IPCC has elaborated a document entitled *"Carbon dioxide capture and storage"* that you can find in the following link: `http://bit.ly/2jy1yFc`.

on the planet.

[2]http://iopscience.iop.org/article/10.1088/1748-9326/8/2/024024

[3]`http://bit.ly/RmSKyb`

[4]http://bit.ly/1Zw7loD

Important! 6.4: Learning more on Climate Change

There is a huge amount of information on climate change. Some examples of interesting materials are this TED talk by former USA vice-president and long-term climate defender Al Gore: `http://bit.ly/1KIdWcK`. **"Before the Flood"** is a documentary produced by Martin Scorsese and featuring Leonardo di Caprio: (Trailer: `http://bit.ly/2dLWpF8`)

Question 6.1: Initiatives to prevent Climate Change

In the previous sections, two landmark agreements (the Kyoto Protocol and the Paris Agreement) have been mentioned. Recently, **COP25** also took place in Madrid. Look for information about the evolution of the concentration of GHGs in recent years. Explain briefly your conclusions on the effectiveness of these agreements **in your own words**.

1.7. Current situation of REs: global context

As the main concepts associated with REs have been already presented, it is now time to take a look at the current situation of REs around the world. **Of particular note is the huge contribution of fossil fuels, with a 79.7 % of the total final energy consumption**[1], as indicated in Figure 1.18. The share of renewable energies sum up to almost 18.1 %, but it is also important to analyze the contribution of each renewable source/technology. Almost half of the total renewable contribution comes from **"traditional biomass"**, which refers to the use of biomass[2] (wood, etc.) in remote and rural places for uses such as heating and cooking. Biomass, geothermal and solar heat[3] (4.2 %) and hydropower (3.6 %) also show important contributions.

It is also interesting to compare these data with those referring to **electricity production** (see Figure 1.19). On the one hand, the **share of RE clearly increases, reaching a significant 26.2 %** of the worlwide electricity production. On the other hand, the contribution of RE technologies is very different, with a remarkable dominance of **hydropower**[4] **(15.8 %)**, followed by **wind power (5.5 %)**, **bio-power (2.2 %)** and **solar photovoltaics (PV)** (2.4 %)[5].

[1] Again, it is important to note that not only electricity is considered here, but also any kind of energy used to cook, to heat, etc.

[2] Biomass is an industrial term for obtaining energy by burning wood, and other organic matter. Burning biomass releases carbon emissions, but has been classed as a renewable energy source in the EU and UN legal frameworks, because plant stocks can be replaced with new growth. It has become popular in coal power stations, which switch from coal to biomass in order to convert to renewable energy generation without wasting the existing generating plant and infrastructure. Biomass most often refers to plants or plant-based materials that are not used for food or feed. As an energy source, biomass can either be used directly via combustion to produce heat, or indirectly after converting it to various forms of biofuel. Source: `https://en.wikipedia.org/wiki/Biomass`

[3] As we are talking about total final energy consumption,the generation of heat (for industrial, transportation or residential uses) is a very important category, as well as electricity production

[4] Hydropower refers to the power derived from the energy of falling water or fast running water.

[5] Solar PV is the renewable energy showing the most remarkable increase: from 1.9 % in 2017 to 2.4 % in 2018.

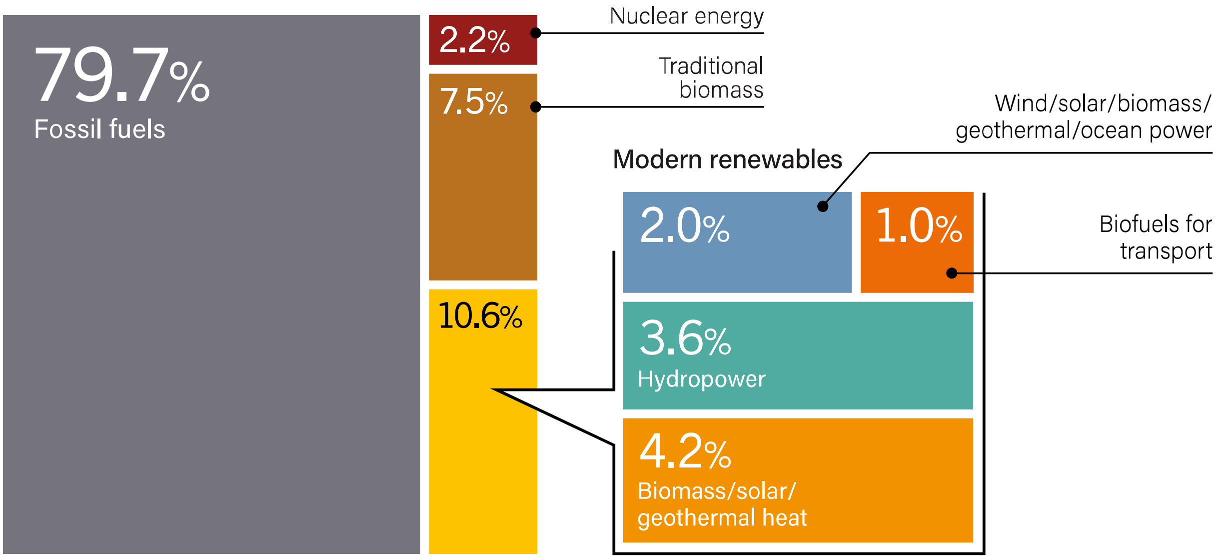

Figure 1.18. Estimated Renewable Energy Share of Total Final Energy Consumption, 2017. Source: REN21 (2019 Report). `http://bit.ly/2rTdoy3`

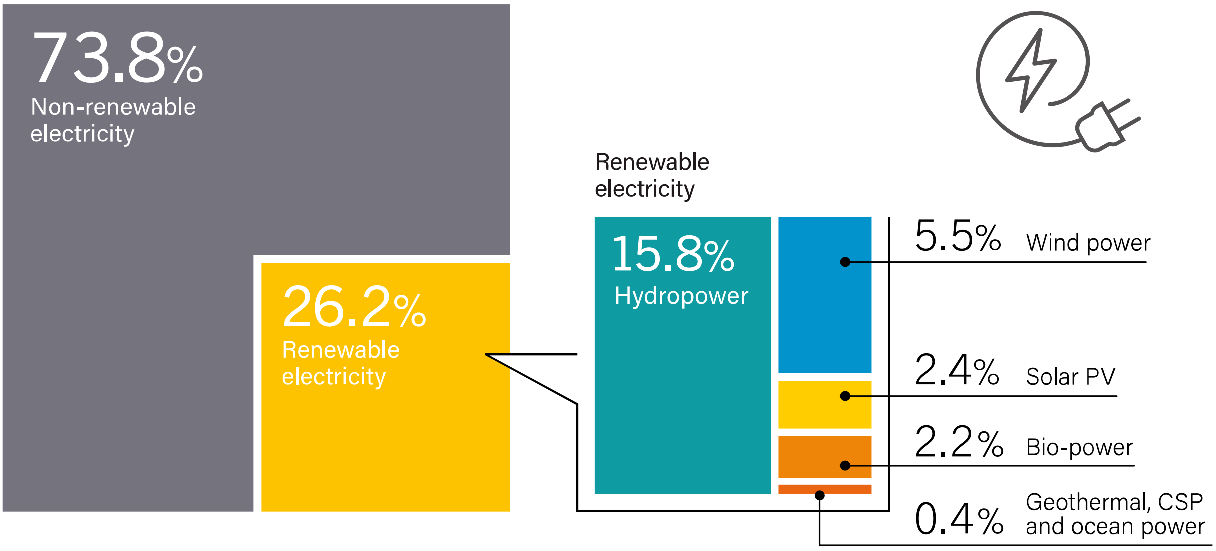

Figure 1.19. Estimated Renewable Energy Share of Total Electricity Production, (end-2018). Source: REN21 (2019 Report). `http://bit.ly/2rTdoy3`

Question 7.1: Evolution of RE share in electricity production

It might be interesting to know the figures associated with RE share in electricity production in previous years. Look for this information referring to 2016 and 2017 (the data in Figure 1.19 refer to 2018), and explain briefly and **in your own words** the conclusions that you reach from looking at these data.

As **RE are emerging technologies**, which, in most cases, have still not reached a full maturity, their evolution in recent years should be also analyzed to get a general overview of the subject. Figure 1.20 shows the investments made in RE technologies in 2018, where **mainly solar and also**

wind power clearly exceed the other technologies. Even if solar power is the tecnology where more investments are focused, it is worth noticing that they have decreased by 22 % in comparison with 2017. The main cause of this effect is to be found in China.

Question 7.2: Evolution of solar PV

The evolution of solar PV is being quite remarkable in recent years. To fully understand the extent of this issue, try to find the corresponding graph of Figure 1.20 for 2016 (REN21 2017 report (`http://bit.ly/2ghNr1A`)) and also 2017 (`https://bit.ly/2KmhGoK`).
Explain briefly **with your own words** your thoughts on the evolution of investments in RE in these years, as well as the detailed cause of the commented decrease in 2018.

The comparison of investments in RE technologies and conventional nuclear and fossil-based technologies, shown in Figure 1.21, reveals a significant balance towards REs that will probably continue growing in future years, with RE technologies clearly dominating the new energy scenario. As stated in the figure, **investment in new renewable power capacity in 2018 was more than twice (65 %) that in fossil fuels and nuclear combined**.

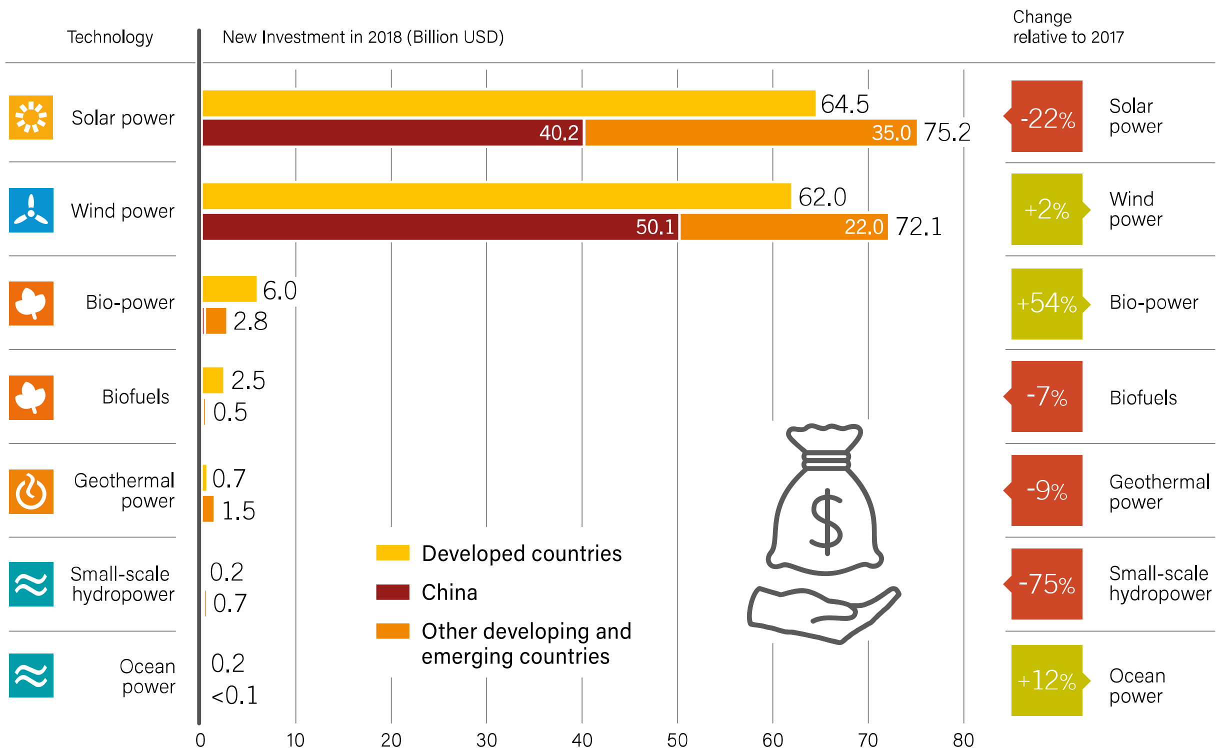

Figure 1.20. Global New Investment in Renewable Energy by Technology (2018). Source: BNEF / REN21 (2019 Report). `http://bit.ly/2rTdoy3`

Question 7.3: Investments in Hydropower

What is the reason behind poor investment in hydropower, particularly taking into account the huge contribution of this technology as indicated in previous figures?
Answer this question briefly **in your own words**.

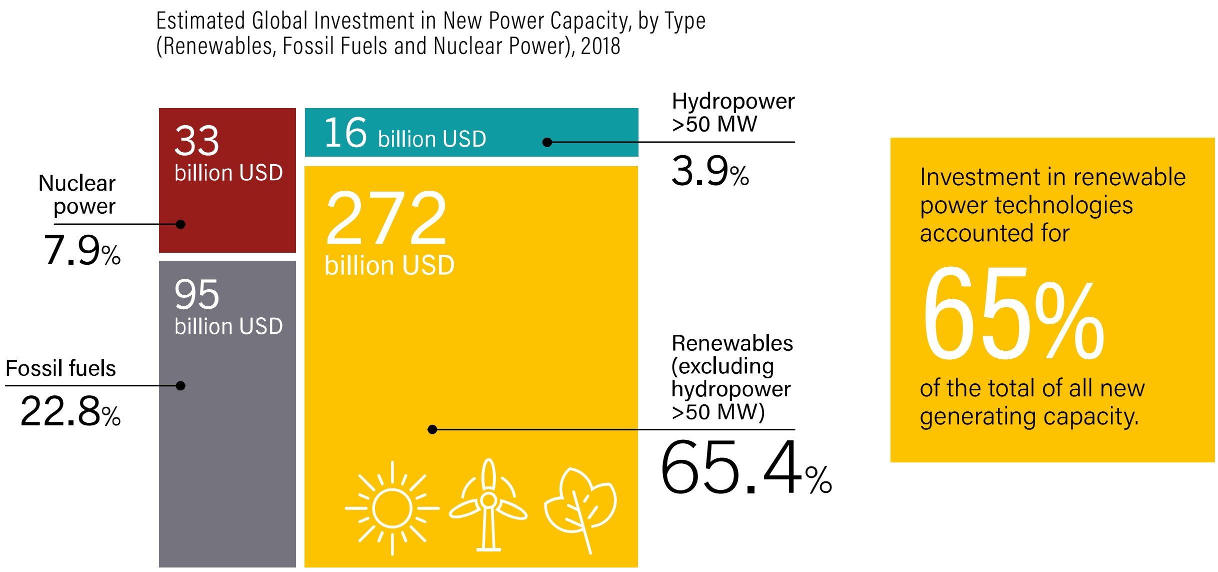

Figure 1.21. Global Investment in New Power Capacity, by Type (Renewable, Fossil Fuel and Nuclear Power), 2018. Source: BNEF / REN21 (2019 Report). `http://bit.ly/2rTdoy3`

Following this brief overview on the current situation of REs, we will now analyze which countries are leading the way in this field. Figure 1.22 shows the top five countries per renewable technology referring to the total capacity installed as of end of 2018.

China and USA are the dominating countries, with **Germany and Japan** also exhibiting remarkable figures. As regards the different technologies, China appears as the first country in hydropower, solar PV and wind power capacities. However, the huge dimensions of this country may lead to a certain distortion of these data. In this regard, the analysis of *per capita*[1] values, may provide additional interesting information. For example, **Germany and Denmark are the first countries in solar PV and wind power capacity *per capita***, respectively. **Spain** appears as the first country in **concentrating solar power (CSP)**[2] and the **fifth country in wind power capacity**.

Question 7.4: REs and Spain

Spain does not appear in the top 6 rank of Figure 1.23, although it is one the main countries in terms of renewable energies.

Try to find information about the possible position of Spain in this classification in previous years and try to justify, **in your own words**, the reasons behind its evolution over the last 5 years.

[1]The total capacity per technology is divided by the number of citizens in the country under analysis.

[2]CSP (also called concentrated solar thermal, and CSP) systems generate solar power by using mirrors or lenses to concentrate a large area of sunlight, or solar thermal energy, onto a small area. Electricity is generated when the concentrated light is converted to heat, which drives a heat engine (usually a steam turbine) connected to an electrical power generator. Source: Wikipedia `https://en.wikipedia.org/wiki/Concentrated_solar_power`

Total Capacity or Generation as of End-2018

	1	2	3	4	5
POWER					
Renewable power capacity (including hydropower)	**China**	United States	Brazil	India	Germany
Renewable power capacity (not including hydropower)	**China**	United States	Germany	India	Japan
Renewable power capacity *per capita* (not including hydropower)[3]	**Iceland**	Denmark	Germany/Sweden		Finland
Bio-power generation	**China**	United States	Brazil	Germany	India
Bio-power capacity	**China**	United States	Brazil	India	Germany
Geothermal power capacity	**United States**	Indonesia	Philippines	Turkey	New Zealand
Hydropower capacity[4]	**China**	Brazil	Canada	United States	Russian Federation
Hydropower generation[4]	**China**	Canada	Brazil	United States	Russian Federation
Solar PV capacity	**China**	United States	Japan	Germany	India
Solar PV capacity *per capita*	**Germany**	Australia	Japan	Belgium	Italy
Concentrating solar thermal power (CSP) capacity	**Spain**	United States	South Africa	Morocco	India
Wind power capacity	**China**	United States	Germany	India	Spain
Wind power capacity *per capita*	**Denmark**	Ireland	Germany	Sweden	Portugal
HEAT					
Solar water heating collector capacity[5]	**China**	United States	Turkey	Germany	Brazil
Solar water heating collector capacity *per capita*	**Barbados**	Austria	Cyprus	Israel	Greece
Geothermal heat output[6]	**China**	Turkey	Iceland	Japan	Hungary

1 Countries considered include only those covered by BloombergNEF; GDP (at purchasing power parity) data for 2017 from World Bank. BloombergNEF data include the following: all biomass and waste-to-energy, geothermal and wind power projects of more than 1 MW; all hydropower projects of between 1 and 50 MW; all solar power projects, with those less than 1 MW (small-scale capacity) estimated separately; all ocean power projects; all biofuel projects with an annual production capacity of 1 million litres or more. Small-scale capacity data used to help calculate investment per unit of GDP cover only those countries investing USD 200 million or more.

2 Solar PV data for India are highly uncertain. See Solar PV section in Market and Industry chapter for details.

3 Per capita renewable power capacity (not including hydropower) ranking based on data gathered from various sources for more than 70 countries and on 2017 population data from the World Bank.

4 Country rankings for hydropower capacity and generation differ because some countries rely on hydropower for baseload supply whereas others use it more to follow the electric load to match peaks in demand.

5 Solar water heating collector rankings for total capacity and per capita are for year-end 2017 and are based on capacity of water (glazed and unglazed) collectors only. Data from International Energy Agency Solar Heating and Cooling Programme. Total capacity rankings are estimated to remain unchanged for year-end 2018.

6 Not including heat pumps. Data are from 2015.

Note: Most rankings are based on absolute amounts of investment, power generation capacity or output, or biofuels production; if done on a basis of per capita, national GDP or other, the rankings would be different for many categories (as seen with per capita rankings for renewable power not including hydropower, solar PV, wind power and solar water heating collector capacity).

Figure 1.22. Top five countries by total capacity or generation as of end-2018. Source: REN21 (2019 Report). `http://bit.ly/2rTdoy3`

A more clear classification is depicted in Figure 1.23, where hydropower has not been included to avoid distorting these data.

As we have already seen, both **solar and wind power** are probably the most prominent new RE technologies, with huge investments being made in the development of new installations and power plants. The specific evolution of these two key RE technologies is very interesting and denotes the growth of REs within the energy sector.

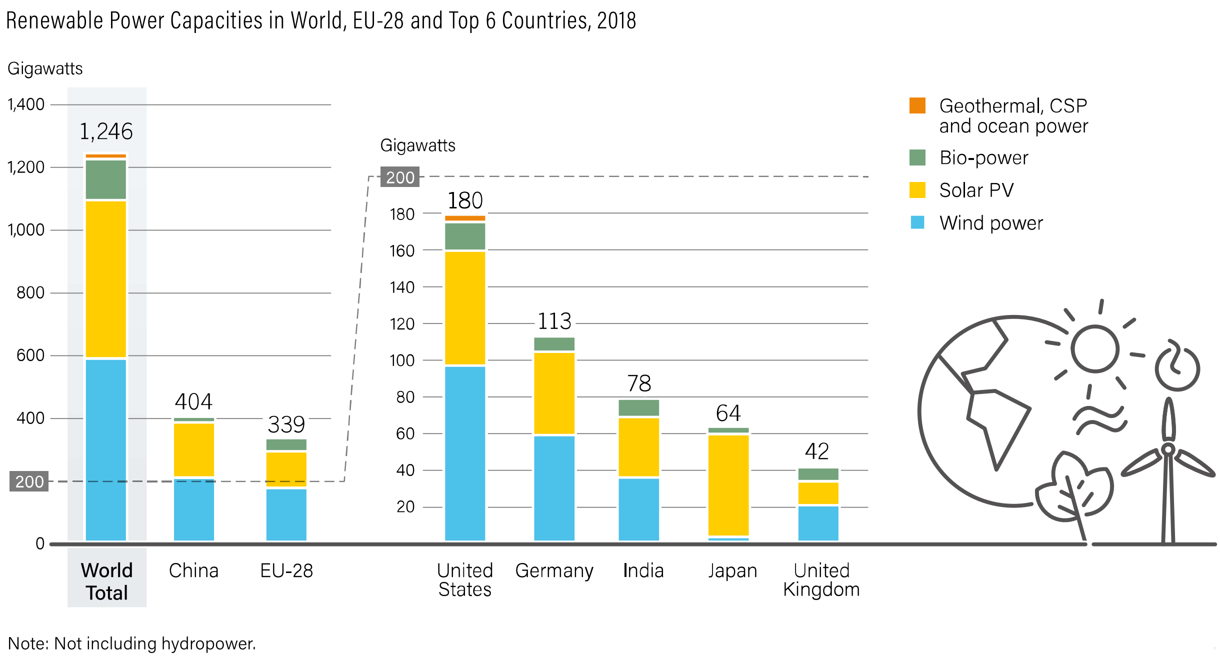

Figure 1.23. Renewable Power Capacities around the World, BRICS, EU-28 and Top 6 Countries, 2018. Source: REN21 (2019 Report). `http://bit.ly/2rTdoy3`

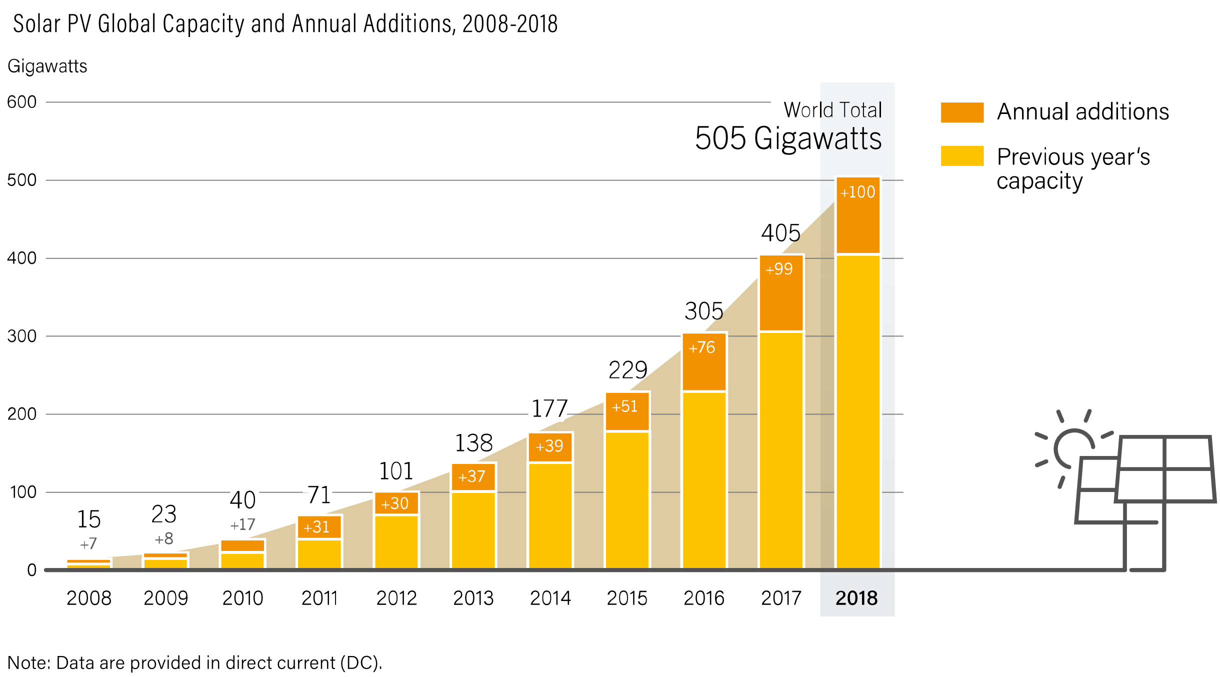

Figure 1.24. Solar PV Global Capacity and Annual Additions, 2008-2018. Source: REN21 (2019 Report). `http://bit.ly/2rTdoy3`

Figure 1.24 shows the evolution of solar PV global capacity , where an **extraordinary growth rate** can be observed. It may also prove useful to determine which countries are leading this trend. Figure 1.25 shows the installed capacity in 2017 and additions in 2018 for different countries. Apart from the incredible development observed in **China**, it is also remarkable to note that growth practically stopped in **Spain**. Among many other reasons, the huge impact of the recent

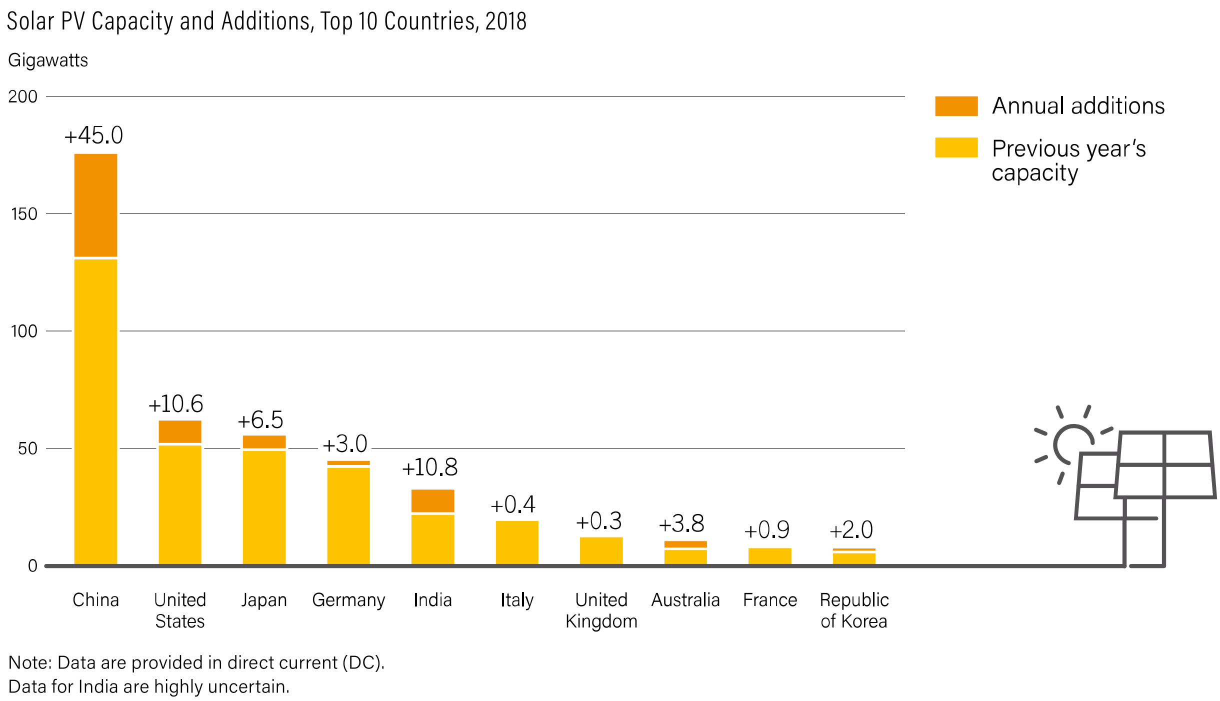

Figure 1.25. Solar PV Capacity and Additions, Top 10 Countries, 2018. Source: REN21 (2019 Report). `http://bit.ly/2rTdoy3`

financial crisis and the instability in policies associated with the development of REs are probably the two main factors explaining this situation[1].

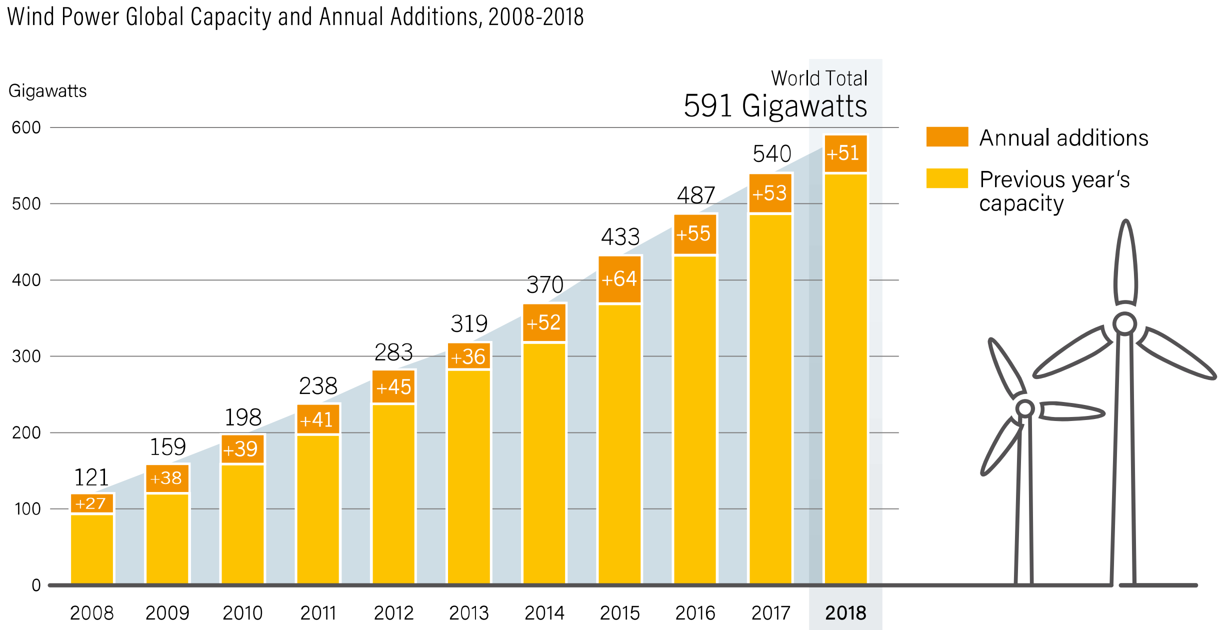

Figure 1.26. Wind Power Global Capacity and Annual Additions, 2008-2018. Source: REN21 (2019 Report). `http://bit.ly/2rTdoy3`

[1] As commented, these data refer to 2018 according to the last reports issued by the main organizations involved in the RE community. However, **the situation in Spain has drastically changed in 2019** as we will comment in following sections.

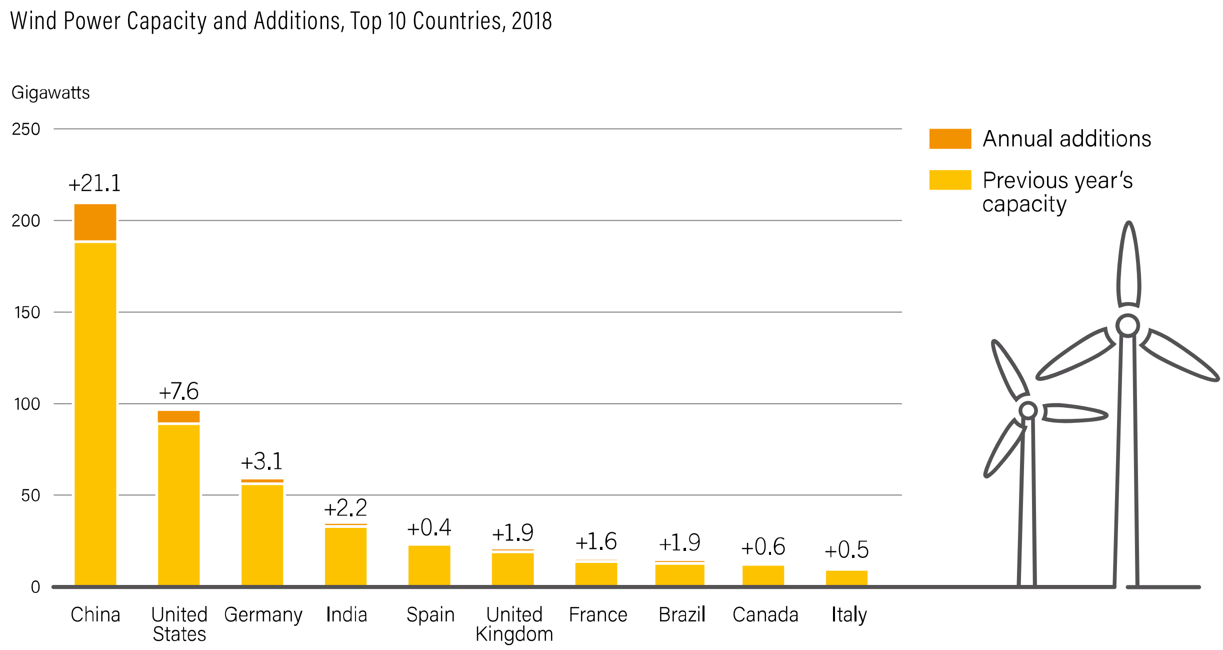

Figure 1.27. Wind Power Capacity and Additions, Top 10 Countries, 2018. Source: REN21 (2019 Report). `http://bit.ly/2rTdoy3`

A similar scenario can be found for **wind power**. Again, the evolution of wind power capacity and the recent evolution by country are shown in Figure 1.26 and Figure 1.27. China is also clearly leading this ranking, followed by the USA. Spain does not show new added capacity in 2018, despite being the 5th country in this category.

Question 7.5: RE evolution in Spain

We have briefly mentioned some possible reasons for this standstill in the development of new RE plants in Spain in recent years.

Search for information about this and try to find specific regulations (Reales Decretos) that have affected the situation in this sector. Give a brief explanation **in your own words**.

1.8. Current situation of REs: European context

As we have just seen, the situation and evolution of REs is completely different depending on the country/region under analysis. The situation in the **European Union (EU)** is determined by its policies that, oriented at stimulating the deployment of these technologies, have fixed two specific goals for the share of total final energy consumption (20 %) and electricity production (40 %). EU countries have established their own objectives, as represented in Figure 1.28 for final energy consumption. In this figure, the RE share of final energy consumption for each country has been indicated in light green (if the 2020 goal has already being reached), while the 2020 goal has been represented by dark green dots.

Some countries have decided to establish more demanding goals (Sweden, Finland, Latvia, Denmark, Austria), although **Iceland and Norway**, which do not appear in the list, would stand out in the list **with current shares of around 80 and 70 %**, respectively. Spain is located at the

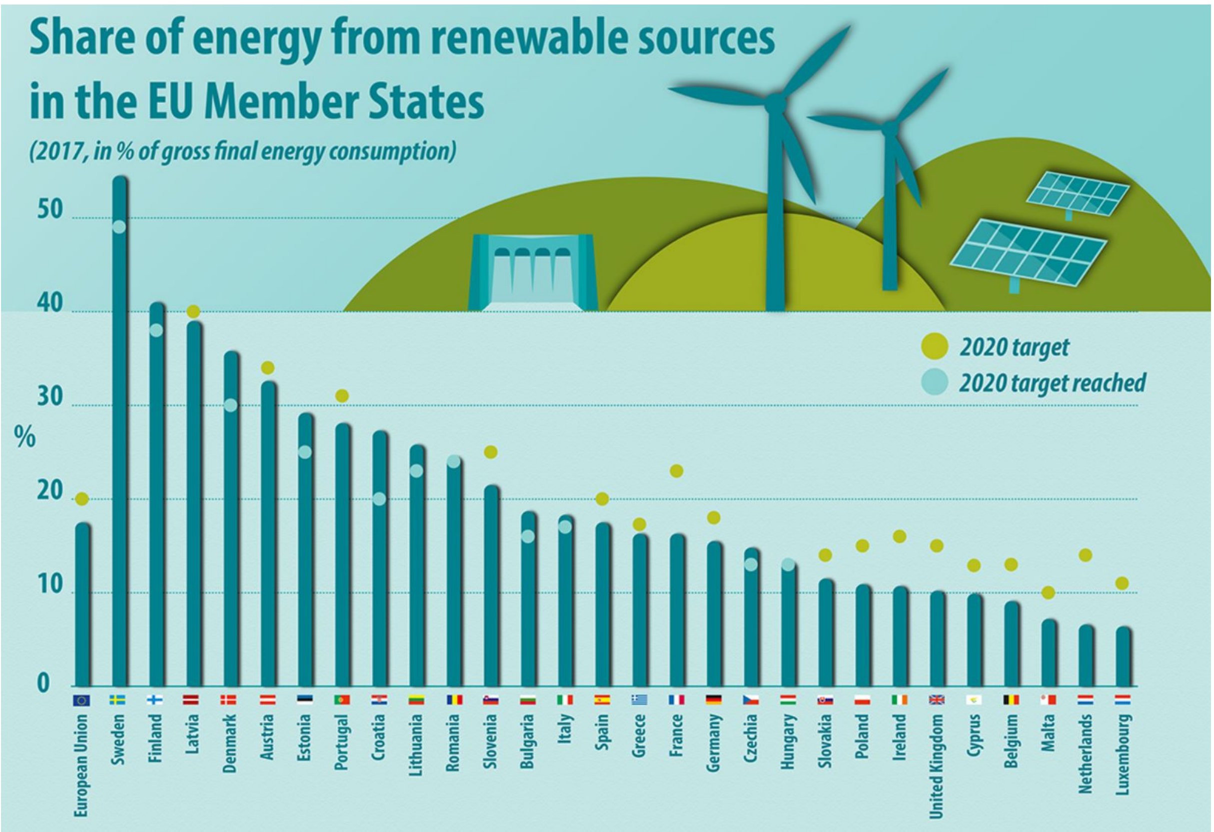

Figure 1.28. RE share of total final energy consumption in EU-28 (2017). Source: Eurostat. `http://bit.ly/2uBLPdq`

midpoint with a goal of 20 % and a current share above 15 %.

Question 8.1: REs in Iceland and Norway

What are the reasons behind the remarkable RE figures of Iceland and Norway?

Search for information and justify, **in your own words**, the **RE shares for final consumption and electricity production in both countries**, indicating the key technologies in each case.

The graph on the left of Figure 1.29 presents the **distribution of EU countries in terms of their shares of renewable energy for the total final consumption**. **Spain** is to be found in the bottom half of the table, with a **12.4 %**.

Figure 1.29 (right) shows the contribution of each energy source to the total final consumption. It is interesting to note that coal (*solid fuels*) has experienced a significant reduction in recent years, with an associate remarkable increase in the RE contribution (13.6 %). **It is worth noting that total final energy consumption and electricity production should always be independently analyzed**. In fact, both the shares of each RE technology and the final contribution will exhibit a significant variation between both parameters.

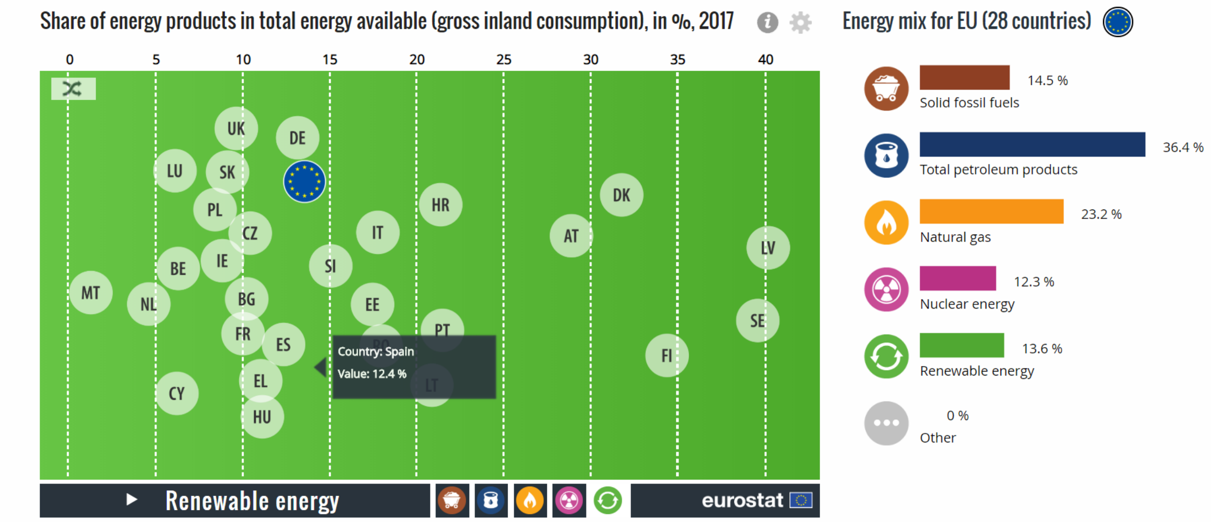

Figure 1.29. Shares of total final energy consumption in UE by energy source (2016). Source: Eurostat.

To illustrate this, Figure 1.30 shows the EU electricity production by source in 2018, where figures for nuclear and RE are clearly different from those presented in Figure 1.29. A very interesting analysis is also shown in Figure 1.31, where the sources of electricity production for each country in the EU are displayed. This graph easily allows to identify situations like the relevance of conventional thermal in different countries, the great contibution of nuclear in France or hydro in Norway, as well as the still low participation of solar PV in electricity generation.

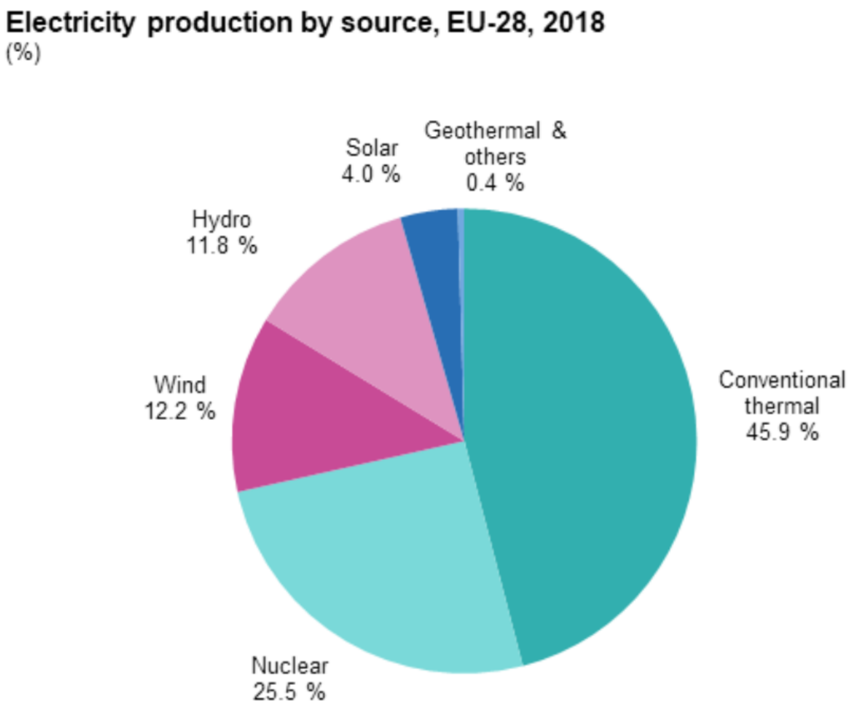

Figure 1.30. EU electricity production by source (2018). Source: Eurostat.

Additionally, Figure 1.32 shows the RE contribution to electricity production in the EU, with Spain reaching 32 % (being the final 2020 goal 40 %) and Nordic countries such as Iceland and

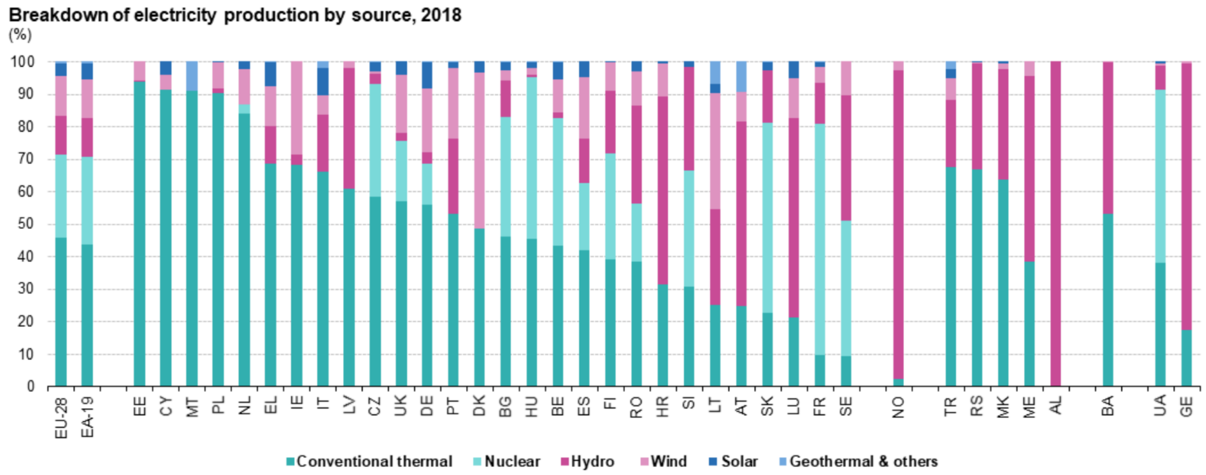

Figure 1.31. EU countries electricity production by source (2018). Source: Eurostat.

Norway reaching impressive figures of ≈ 100 %.

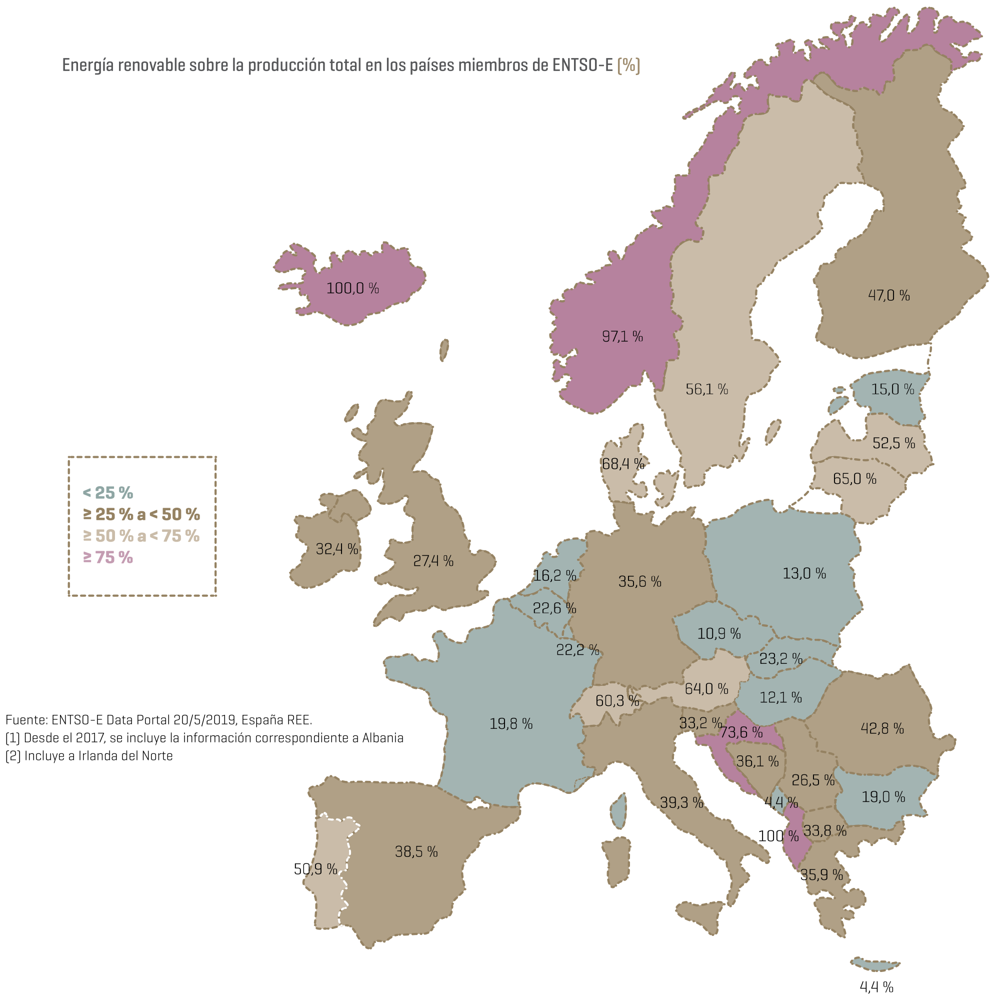

Figure 1.32. RE contribution to the EU electricity production (2018). Source: REE (El sistema eléctrico español 2018). `http://bit.ly/2t9Kb2q`

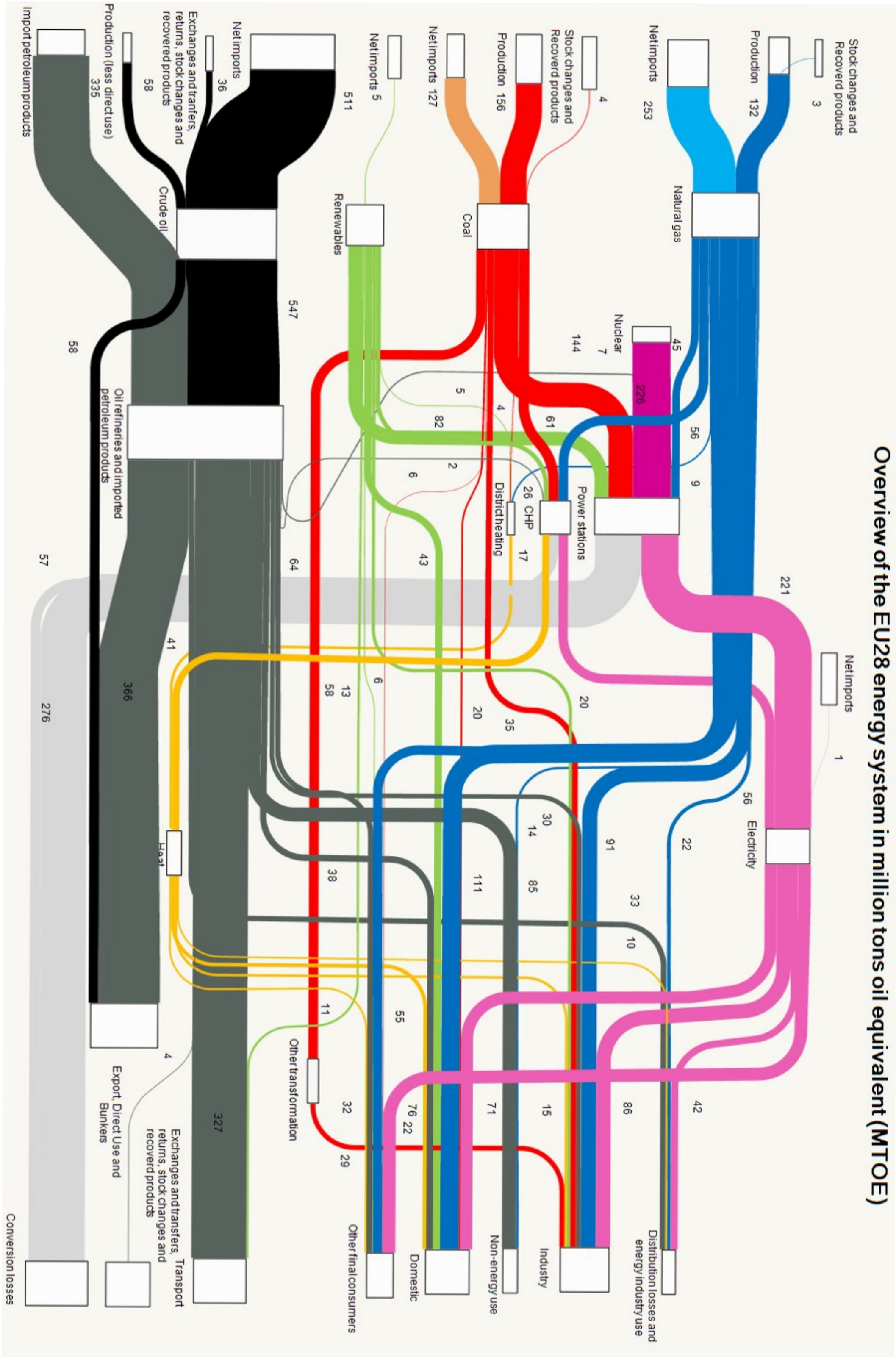

Figure 1.33. Sankey diagram of the Europen energy sector. Source: Statistical Office of the European Union (Eurostat). `http://bit.ly/2AsEGu0`

Question 8.2: EU Energy System: Sankey Diagram

The Sankey diagram of the UE Energy System is the perfect tool for completing the study presented in this section.

Look at this diagram Figure 1.33 (http://bit.ly/2AsEGu0) and answer the following questions:

a) What does the concept *net imports* refer to?

b) What is *district heating*?

c) What is the reason for the existence of *conversion losses*?

1.9. Current situation of REs: Spanish context

Politics and legislation concerning REs in Spain can be understood within the EU framework. Spain has established a RE share of 20.8 % for final energy consumption and 40 % for electricity generation. This evolution has been depicted in Figure 1.34. The trend in recent years has been positive, with an increase from 16.2 in 2015 to 17.4 % in 2016 and 17.5 % in 2017. [1]

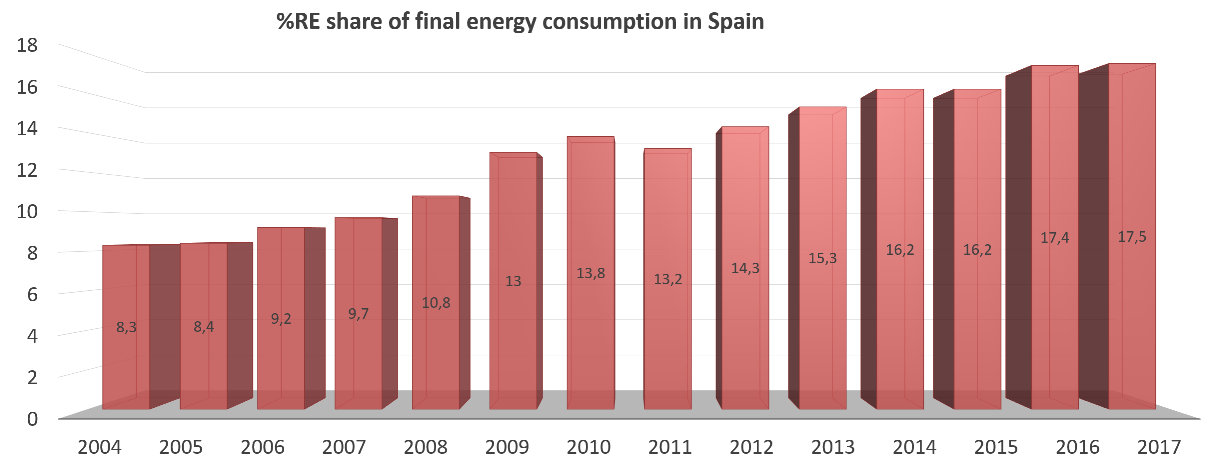

Figure 1.34. RE share of final energy consumption in Spain. Source: Eurostat (https://bit.ly/2B07VGK). Elaboración propia.

In the context of climate change previously explained in this course, these variations in RE share have a direct influence on GHG emissions. See for example the evolution of RE and non-RE contribution to electricity production in Spain over recent years (Figure 1.35): there is a clear decrease in RE contribution in 2015 and 2017, which is directly correlated with the evolution of CO2 emissions (derived from electricity generation) in Figure 1.36. **Offical data for 2019 has not been released yet**, but it is known that there will be **a decrease of the RE contribution to 36.8 %**, with a significant decrease in hydro production, from 13.1 % (2018) to 9.0 % (2019), and a subtle increase in both wind and solar, as indicated in Figure 1.37, which depicts data for 2019 advanced by REE.

[1] It is worth noting that data associated with primary energy or final energy consumption is more difficult to gather than other energy statistics, that is the reason why these data usually refer to previous years. For more info: http://bit.ly/2CbWD04.

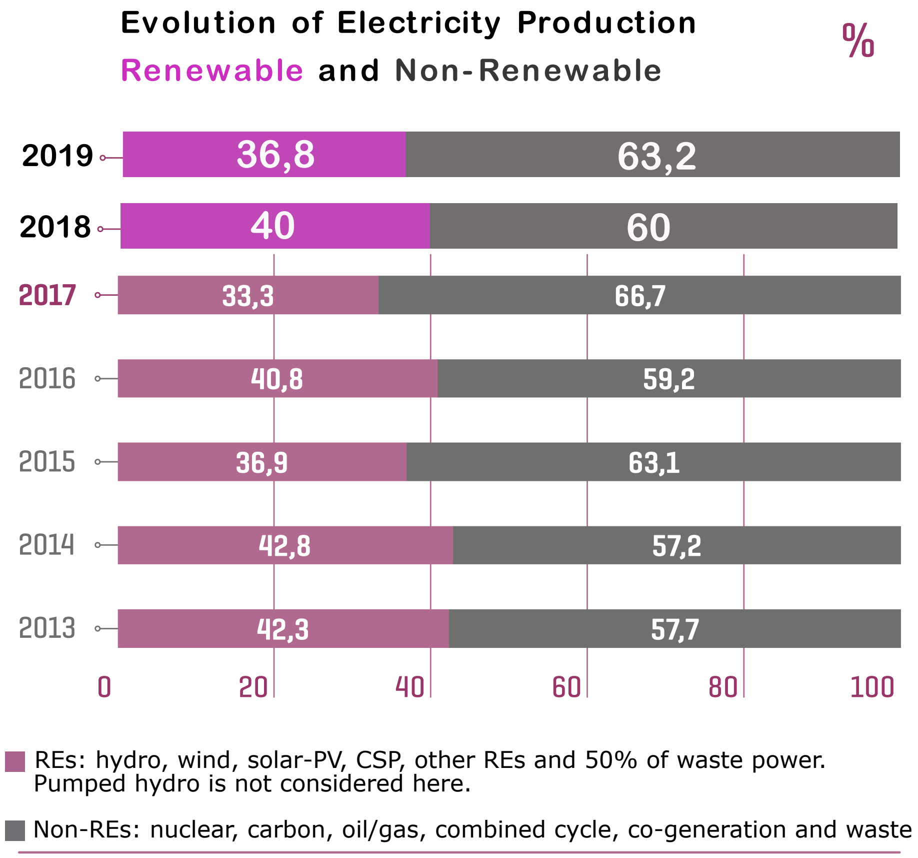

Figure 1.35. Evolution of RE and non-RE shares of electricity production in Spain (as of end 2019). Source: REE: *"El sistema eléctrico español 2017"* and *"El sistema eléctrico español: previsión de cierre 2018"* . `http://bit.ly/2sVemHV` and `https://bit.ly/2UcyfVl`

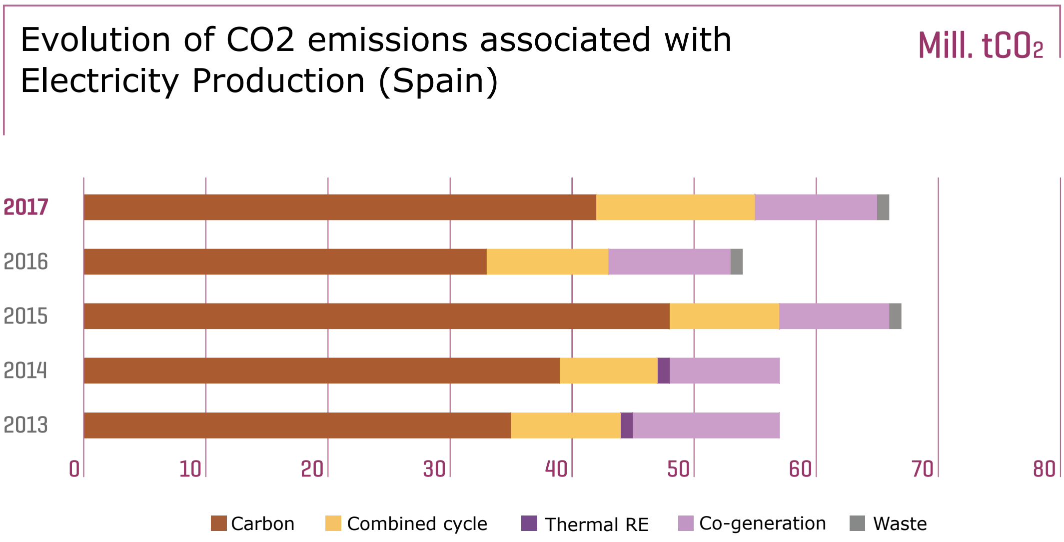

Figure 1.36. Evolution of CO2 emissions associated with electricity production in Spain (as of end 2017). Source: REE: *"El sistema eléctrico español 2017"*. `http://bit.ly/2sVemHV`

Even if the RE contribution to the electricity generation in Spain has decreased, CO2 emissions are expected to show a subtle decrease, as the share of generations free of emissions has decreased

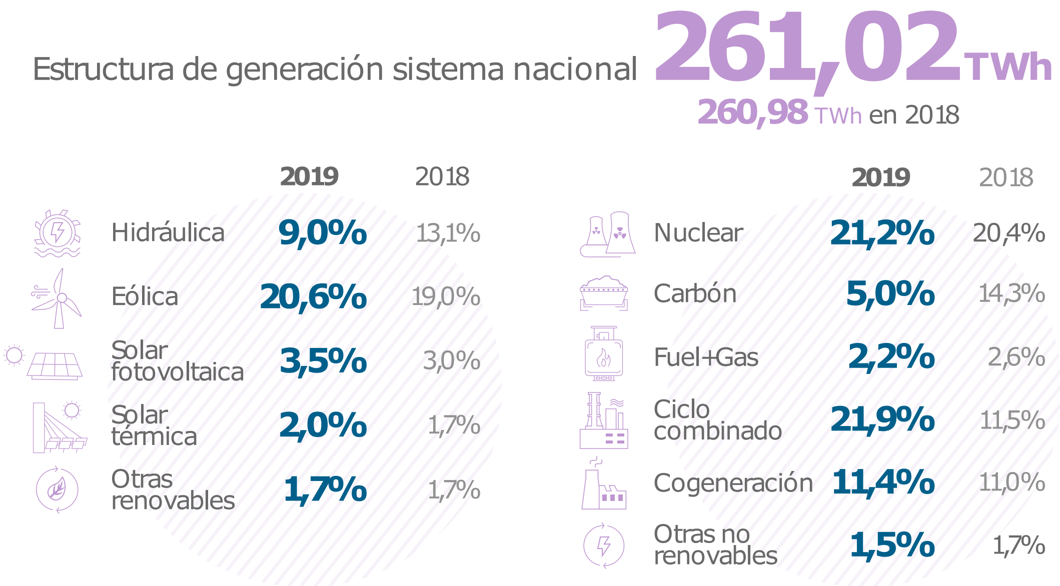

Figure 1.37. Electricity generation in Spain (2019). Source: "Previsión de cierre del sistema eléctrico español 2019" `http://bit.ly/2sJQPw7`

from 59.7 to 58.6 %. This could be explained by the increase in the nuclear power contribution, from 20.4 (2018) to 21.2 % (2019).

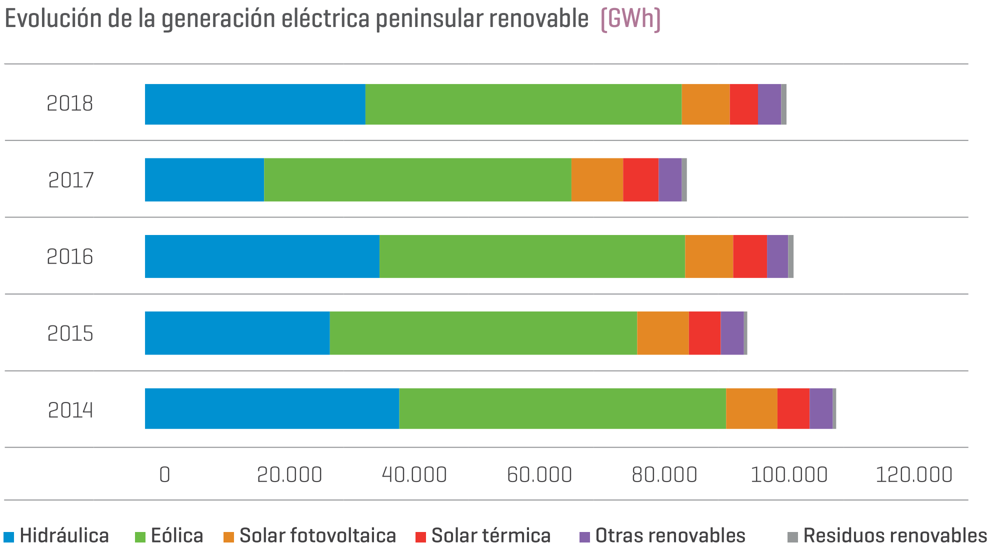

Figure 1.38. Evolution of RE generation in Spain by technology (as of end 2018). Source: REE: *"Avance del informe del sistema eléctrico español 2018"*. `http://bit.ly/2sVemHV`

Figures 1.38 and 1.39 present the evolution of both RE and non-RE technologies (as of end 2018), where it seems clear that that decrease in RE contribution in 2015 and 2017 was mainly due to the drop in hydro-power that was compensated for mainly by coal.

1.9.1. Spain 2019: a new scenario!

As already commented in previous sections, **Spain has suffered several years of a complete standstill** in the development of new installations associated with modern REs, mainly wind and

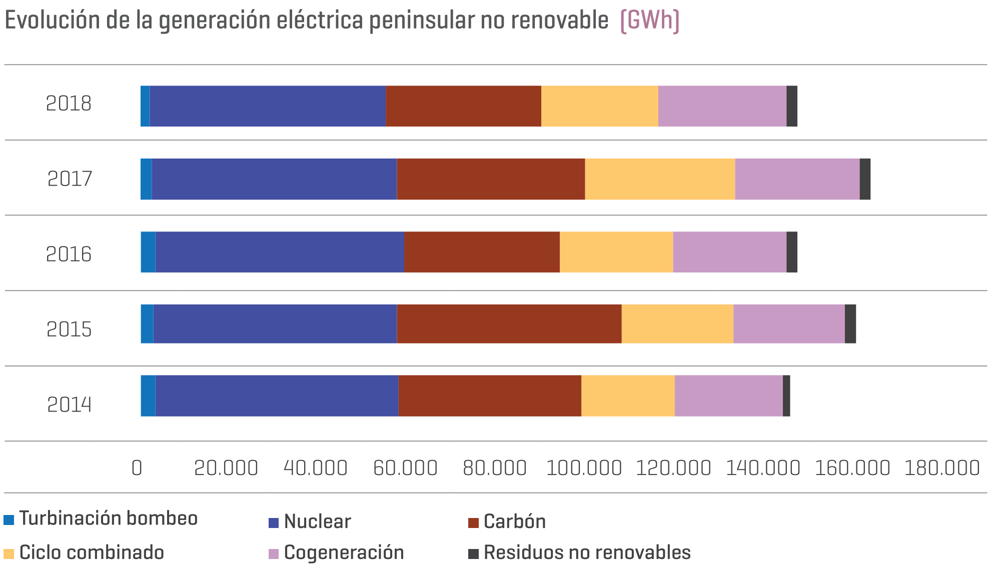

Figure 1.39. Evolution of non-RE generation in Spain by technology (as of end 2018). Source: REE: *"Avance del informe del sistema eléctrico español 2018"*. `http://bit.ly/2sVemHV`

solar PV. **This scenario has radically changed in 2019 with a huge increase in solar PV capacity, as well as in wind power**[1]. This situation will be explained in detail in the following chapters devoted to solar PV and wind power, but it is worth commenting some of the associated reasons:

- Several GW of (mainly) solar PV and wind power were awarded in auctions in 2017 and should be installed before the end of 2019.
- Several installations have been deployed without being associated to auctions, which indicates that solar PV (and, of course, wind power) are already competitive in terms of costs compared to traditional technologies as those derived from fossil fuels
- New regulations have also estimulated this activity, for example related to self-consumption solar PV installations

1.9.2. Current situation of REs: Conclusions

The current situation of REs in the global, European and Spanish contexts has been addressed in the previous sections. The main RE technologies in terms of their contribution to the total final consumption and electricity production have been identified. In addition, RE evolution over recent years has been analyzed, noticing a remarkable increase in their overall contribution. It seems clear that traditional hydro, but also modern solar PV, CSP and wind technologies, among others, will play a major role in the energy sector in future decades.

The development of REs, which faces technological, environmental and political challenges, is an exciting field of research and development. Before studying the close relationship between REs and telecommunications, two key issues must be dealt with: **RE policies and energy storage technologies** (in the power grid).

[1] As many of these installations were finished at the end of 2019, this doesn't imply an increase in PV generation, which will surely happen in 2020.

1.10. RE policies

The main concepts concerning REs have been already introduced in this course. It is now time to try to answer the following questions:

Are REs really necessary? Yes, especially if we want to achieve a **decarbonization**[1] of our society and, in particular, of the energy and transport sectors.

What advantages do REs provide? **Sustainable development**, which seems impossible with the current exploitation of fossil fuels.

Are there any disadvantages associated with REs? That's out of the question! The dependency on their corresponding energy sources (wind, solar radiation, etc.) and their associated intermittency, which prevents a scheduled and controlled production (to a certain extent). Moreover, RE technologies are, in some cases, not mature enough to compete (without subsidies or similar) with traditional fossil-based technologies.

Why is a 100 % RE system still a long way from becoming a reality? The transition to a fully renewable energy system is far from easy. On the one hand, it is necessary to harvest the required resources (solar radiation, wind, waves, etc.). On the other hand, some of these technologies are still more expensive than traditional ones (see ***grid parity*** in the box below). The inherent RE intermittency has to be compensated for with other technologies (such as nuclear) or storage solutions able to manage large amounts of energy[2]

Who pays the extra cost (if any) of REs This is a very pertinent question and very important in Spain, for example. REs needed (and some, like those derived from Ocean Power, for example, will need) an initial push, as they were technologies a long way off maturity and subsidized policies were necessary. For example, some years ago (let's say 2007-8) a solar PV plant was not profitable, given that the cost of PV modules was much higher than today. In those times, some governments decided to stimulate the deployment of these power plants by offering subsidies[3]

Important! 10.1: Grid Parity

Grid parity occurs when an alternative energy source can generate power at a **levelized cost of energy (LCOE)** that is less than or equal to the price of purchasing power from the electricity grid. The term is most commonly used when discussing renewable energy sources, notably solar power and wind power (Source: Wikipedia).

[1] Decarbonization implies, not only discontinuing carbon as an energy source, but also gas and oil (fossil fuels in general).

[2] Here energy storage refers to large-scale deployments, not home-based solutions such as small batteries.

[3] In Spanish often referred to as: *"primas" a las renovables*.

Important! 10.2: LCOE: Levelized Cost of Energy

LCOE is a parameter that allows making a direct comparison between different energy technologies, as it measures the lifetime costs of a given power plant (cost of building, operation, etc.) divided by the energy production. Its units are $\$/Wh$.

Question 10.1: Are REs really that necessary?

In the context of this course we take for granted the importance and relevance of REs in the present and near future of the global energy landscape.

However, of course, there are dissenting voices, as with the following TED talk: `https://youtu.be/N-yALPEpV4w`.

After watching the talk, briefly summarize the Shellenberger's opinion, the main drawbacks of the EERR according to his opinion, and your own vision about it: do you share the opinion expressed in this TED talk?

Figure 1.40. Charla TED *"Why renewables can't save the planet"*. Fuente: YouTube `https://youtu.be/N-yALPEpV4w`

1.10.1. Renewable Subsidies

Renewable subsidies (the so-called *"primas" a las renovables* in Spanish) are a special payment system created to stimulate the development and implementation of some RE technologies in each contry.

The idea is simple: let's assume that we are in the year 2007 and we want to stimulate the development of power plants based on a given (renewable) technology. This technology is still not profitable for private companies and, therefore, these subsidies are necessary to establish an interesting compensation. Otherwise, these companies will still go on developing traditional fossil fuel-based plants, more mature and with a faster return of the economic investment. In this manner, governments can establish a subsidized system were companies are ensured that each generated kWh will be paid for at a price above grid parity (average cost of electricity).

Many countries, such as Spain, Italy, Germany and so on, adopted this system.

Let's see the case of Spain in detail: Royal Decrees (Real Decreto: RD) **661/2007 and 1578/2008** established the special payment system for **REs and also for co-generation** (see Figure 1.41). In RD-2008, the highest payment was set for solar PV, where a classification was established in terms of the capacity of the plant and its type: **rooftop**or **ground-mounted**.

RD 661/2007

Energy Source	Feed-in Tariff
Biomass and biogas	up to 13.06 c€/kWh for the first 15 years
Cogeneration systems	maximum FiT of 13.29c€/kWh during lifetime of system.
Geothermal, wave, tidal and sea-thermal	6.89 c€/kWh for the first 20 years
Hydroelectric	7.8 c€/kWh for the first 25 years
Solar thermoelectric	26.94 c€/kWh for the first 25 years
Waste combustion	up to 12.57 c€/kWh for the first 15 years
Wind systems	up to 7.32 c€/kWh for the first 20 years

RD 1578/2008

Rooftop/BIPV		**Ground-mounted**		**Term**
Size	**Incentive**	**Size**	**Incentive**	
1-20kW	0.34€/kWh	1-10MW	0.32€/kWh	25 años
20kW-2MW	0.31€/kWh			

Figure 1.41. Subsidies for REs according to RD 661/2007 and 1578/2008. License: Jesus Mirapeix.

Looking at the figures, a question arises: are these payments too high or too low? Now we know the answer, although it has been affected by several factors, like the recent financial crisis. These payments were too high, forcing the following governments to cut these subsidies, thus generating a significant instability in the sector.

At this point, it might prove interesting to briefly compare the situation in Spain with other countries that followed the same policies. A good example is Italy, whose solar PV subsidies were categorized in terms of capacity (size), innovative technologies and **self-consumption** and **feed-in** installation[1] (Figure 1.42). It can be observed how the Italian subsidies were considerably lower than those offered in Spain. In this regard, it is very interesting to analyze the evolution of the total capacity installed in both countries (see Figure 1.43). In 2009, Spain was in second place worldwide, but its capacity has not shown the same development as in other countries. For example, Italy now has around four times the capacity installed in Spain.

[1] A self-consumption installation is designed to provide energy to the building/system where it is located, for example a single-family home. On the contrary, a feed-in installation operates as a power plant, generating energy and injecting it into the power grid for its distribution.

Standard self-consumption tariff

Rooftop/BIPV		Ground-mounted		Term
Size	Incentive	Size	Incentive	
1-3kW	0.100€/kWh	1-3kW	0.094€/kWh	20 years
3-20kW	0.089€/kWh	3-20kW	0.083€/kWh	20 years
20-200kW	0.075€/kWh	20-200kW	0.069€/kWh	20 years
200kW-1MW	0.048€/kWh	200kW-1MW	0.042€/kWh	20 years
1MW-5MW	0.036€/kWh	1MW-5MW	0.031€/kWh	20 years
5MW+	0.030€/kWh	5MW+	0.024€/kWh	20 years

Standard feed-in tariff

Rooftop/BIPV		Ground-mounted		Term
Size	Incentive	Size	Incentive	
1-3kW	0.182€/kWh	1-3kW	0.176€/kWh	20 years
3-20kW	0.171€/kWh	3-20kW	0.165€/kWh	20 years
20-200kW	0.157€/kWh	20-200kW	0.151€/kWh	20 years
200kW-1MW	0.130€/kWh	200kW-1MW	0.124€/kWh	20 years
1MW-5MW	0.118€/kWh	1MW-5MW	0.113€/kWh	20 years
5MW+	0.112€/kWh	5MW+	0.106€/kWh	20 years

Figure 1.42. Subsidies for solar PV installations in Italy. Source: Eurostat. License: Jesus Mirapeix.

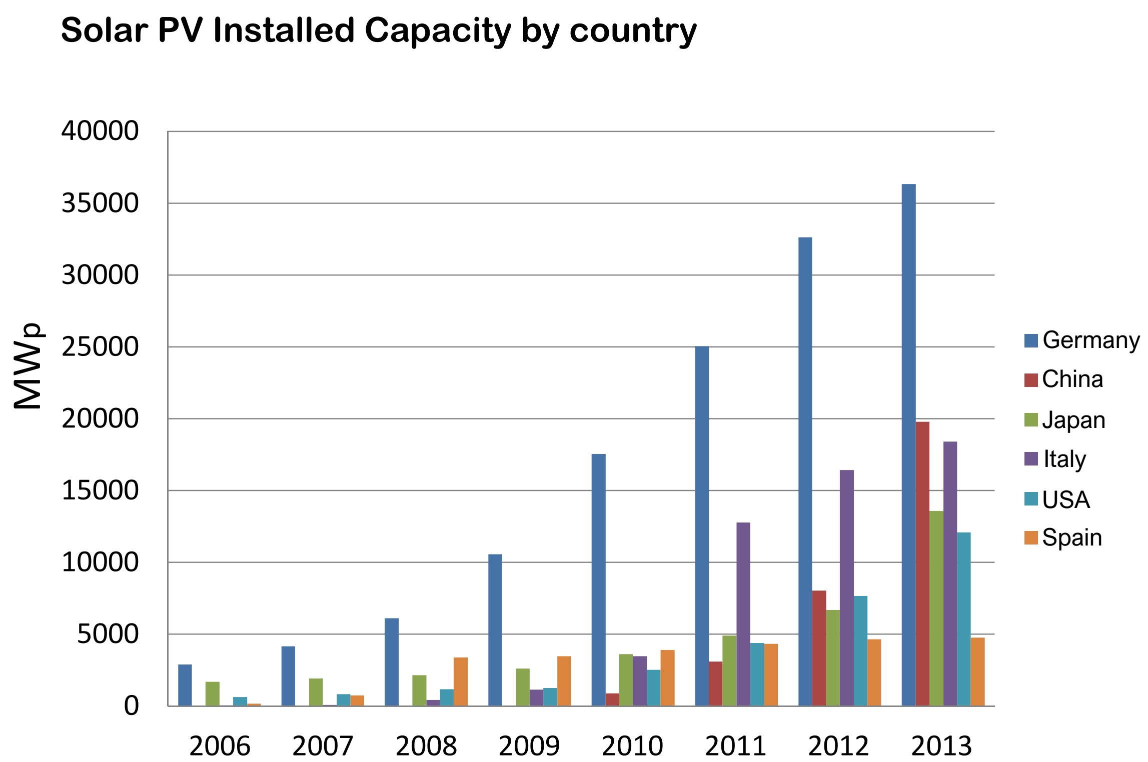

Figure 1.43. Evolution of global solar PV capacity by country. Source: Eurostat. License: Jesus Mirapeix.

As already commented, and as we will see in the chapter devoted to solar PV, **the situation regarding new PV additions (and, to some extent, new wind capacity) has drastically changed**

in Spain in 2019, with more than 3 GW added during that year (as of end November, 2019). This new landscape is, in a way, related to the regulation provided by **RDL 15/2018** and **RD 244/2019**.

Question 10.2: Solar PV subsidies

Do some research regarding this new regulation (RDL 15/2018 and RD 244/2019) and try to find out if there are subsudies for these new installations deployed in 2019 in Spain.

1.10.2. Electricity Market in Spain

Regulation of the electricity market establishes the way that electricity is traded, thus affecting the development of REs and the final price of electricity. How does this market operate in Spain? It is managed by OMEL (Operador del Mercado de Electricidad). 80 % of electricity is generated by these 5 major companies: Endesa, Iberdrola, Union Fenosa, EdP and Viesgo. Red Eléctrica Española (REE) is the corporation that operates the national power transmission system of the electricity grid in Spain. Distribution and commercialization is carried out (90 %) by branches of the 5 companies mentioned above.

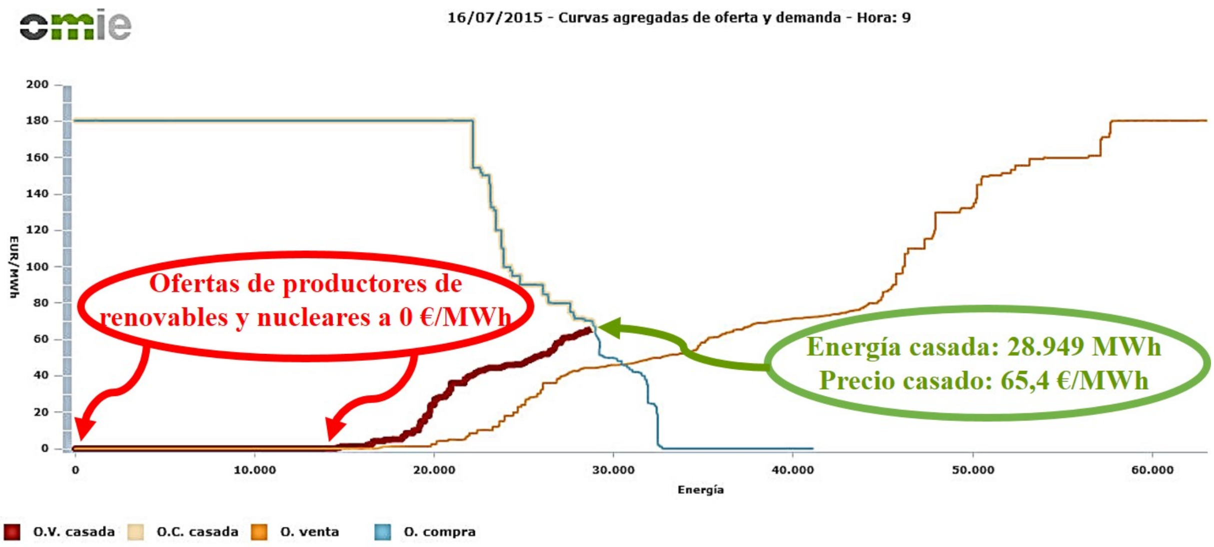

Figure 1.44. Example of electricity bid (July 16, 2015. 09:00AM) Offer and demand curves (sell and buy orders in brown and blue, respectively). Source: blog Publico (Original Source: OMIE) `http://bit.ly/1OlfrdJ`

OMEL operates the daily bid to establish the electricity prices for the next 24 hours: how does this bid work?

The highest priority in this bid is assigned to nuclear plants, given that the adjustment of production in these plants would be highly expensive. REs are assigned the second highest priority, in an attempt to stimulate their development and due to the impossibility of storing the associated fuel (wind, solar radiation, etc.). REs are assigned a given price of 0, thus generating a reduction in the final price of the bid. It is worth noting that not only REs, but also co-generation and waste follow this system. The last energy source that covers the demand establishes the **"marginal price"**, the one that is used to pay all the energy sources that have participated in the bid. In this way, nuclear plants and hydro-power plants, for example, receive incomes that exceed their costs, given that they are old plants, whose amortization was probably accomplished years ago. Additionally, if the demand is low and the production via nuclear and RE technologies is high, the final price of the bid might be 0.

Figure 1.45. Trump imposes tariffs on solar imports (January-2018). Source: Bloomberg. `https://bloom.bg/2GmZ03g`

Important! 10.3: Trump: Tariffs on Solar Imports

A good and very recent example of policies related to renewable energies is the decision taken by Trump's administration of imposing a **30 % tax on every import related to solar energy**. This measure is supposed to protect and promote USA jobs and companies associated with the PV sector. However, some experts claim that the result will be precisely the opposite, as prices will increase and the consumers will be therefore affected.

1.11. Energy Storage in the Power Grid

One of the missions of REE is to forecast the electricity demand and to perform an on-line real-time monitoring of production and transmission to ensure that there is always a **perfect balance between demand and production**. If variations are detected, real-time commands are sent to specific plants (e.g. wind-power plants, whose production can be easily regulated). Figure 1.46 shows the evolution of production for January 12, 2020, while Figure 1.47 shows the detailed evolution of the production by source. Nuclear power shows a significant production (25.68 % at 15:20), followed by combined-cycle (16.33 %) and solar PV (16.24 %) of the total production.

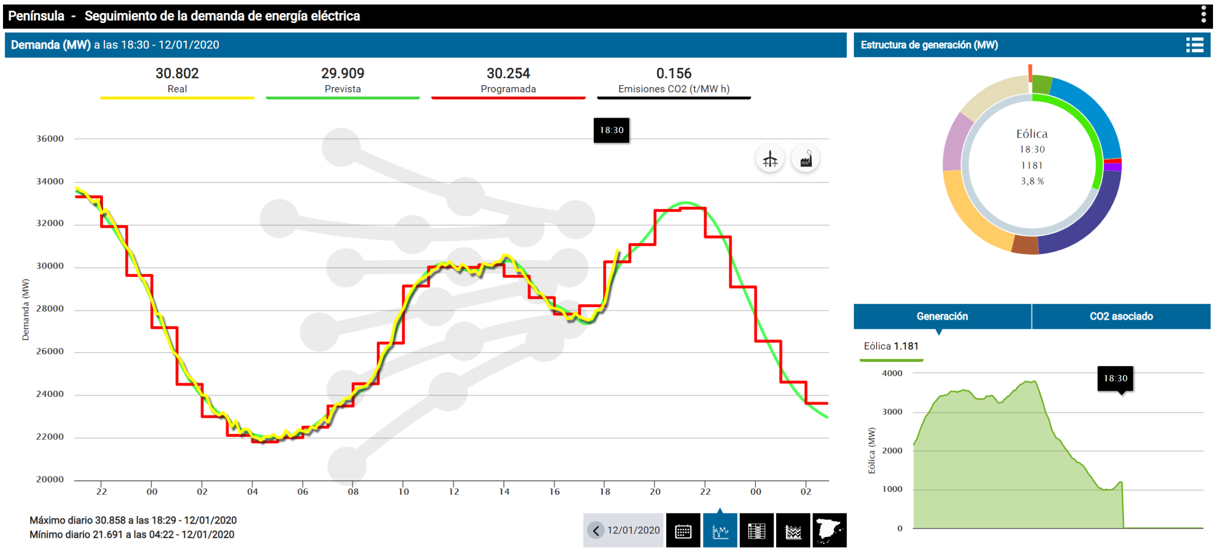

Figure 1.46. Example of real-time information provided by the REE on demand and production in Spain: January 12, 2020). Source: REE.

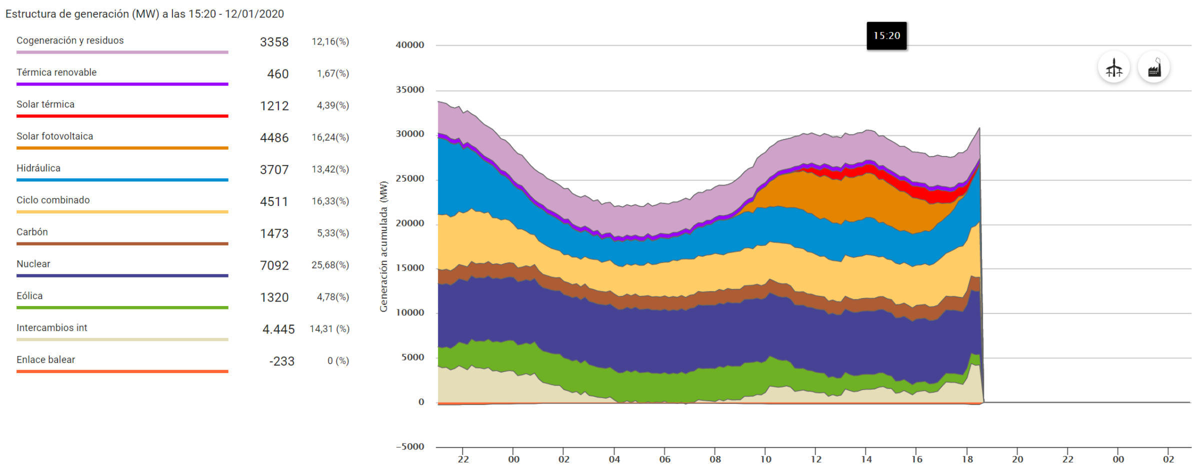

Figure 1.47. Evolution of electricity production in Spain: January 12, 2020. Source: REE

The process described above is necessary because there is a **lack of technologies allowing large-scale energy storage in the power grid**. This is also a serious drawback for the development of REs, given the inherent intermittency of some key technologies, like solar and wind.

Let's take the example of wind-power: instead of being forced to regulate production on windy days, it would be ideal to be able to store excess energy for later use. The concept of **Capacity Assurance** (*Garantía de Capacidad* in Spanish) is important in this context, as it refers to the reliability of a given technology to provide its installed capacity (nominal power) at a given moment (see Figure 1.48). As expected, solar PV and wind power, technologies whose sources exhibit important fluctuations, show low capacity assurances.

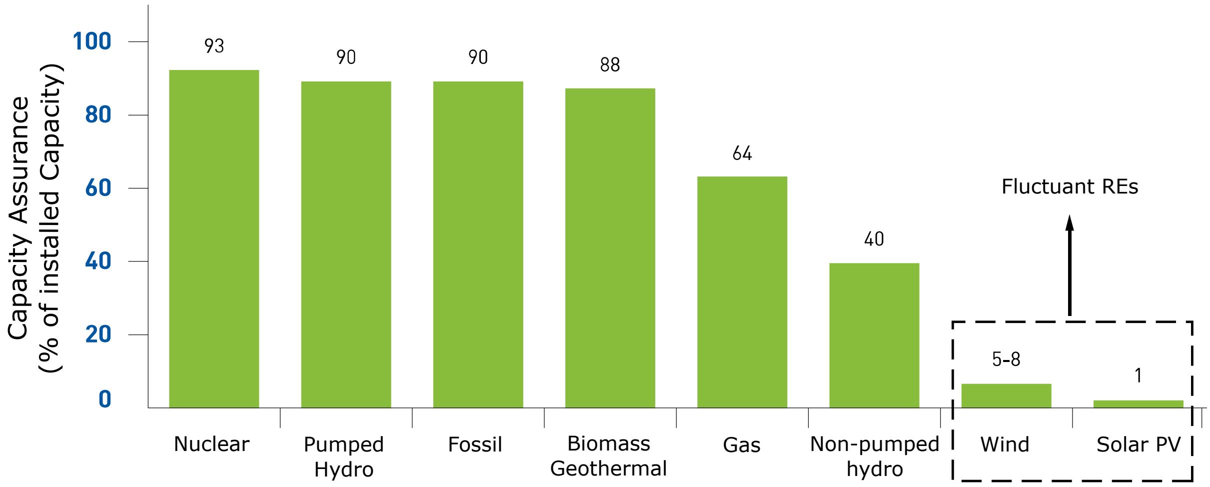

Figure 1.48. Capacity Assurance associated with electricity production technologies. Source: IDAE (*Evolución tecnológica y prospectiva de costes de las EERR*) `http://bit.ly/2nRALmR`

Supported by the increasing relevance of REs, interest in new large-scale storage solutions has risen in recent years, with several alternatives under analysis. It is worth noting that, nowadays, **pumped-hydro** is the only relevant large-scale storage technology used in the power grid.

Question 11.1: Pumped-hydro plants

How many pumped-hydro plants are there in Spain? Search for this information and, if possible, find also the associated capacity of these plants.

The IDAE document "Evolución tecnológica y prospectiva de costes de las EERR" presents an interesting study on these storage technologies, where 4 different categories are established: **mechanical, thermal, electromagnetic and electrochemical** storage (see Figure 1.49).

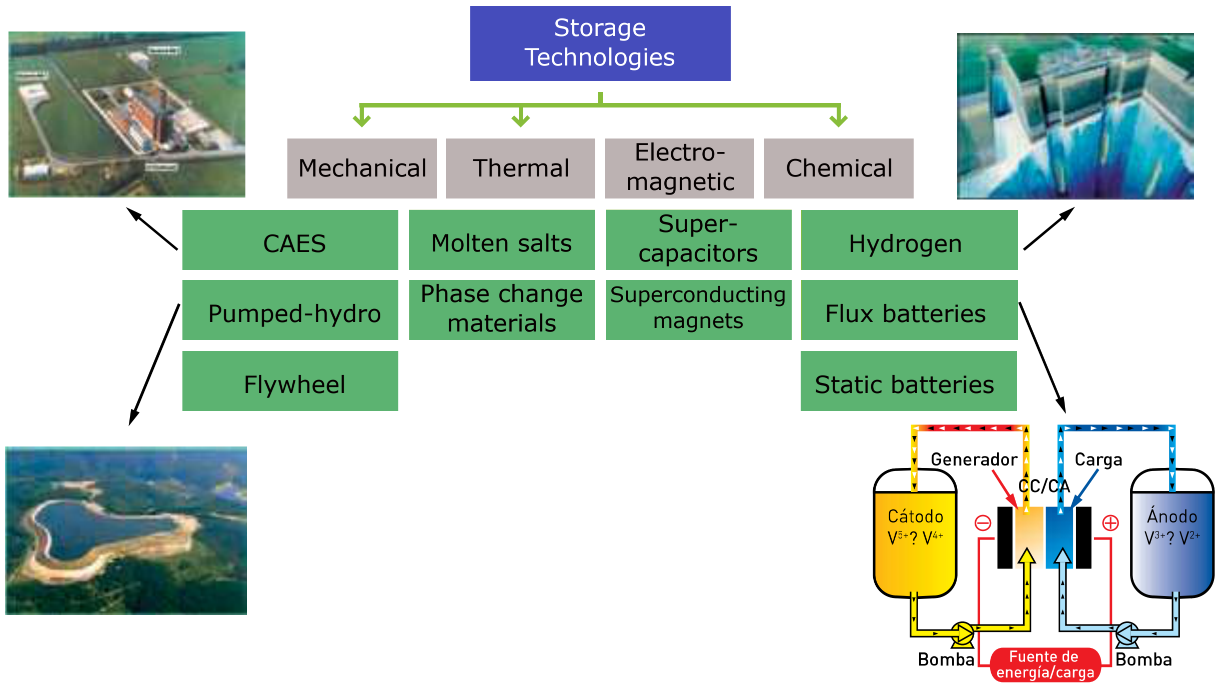

Figure 1.49. Large-scale storage solutions. Source: IDAE (*Evolución tecnológica y prospectiva de costes de las EERR*) `http://bit.ly/2nRALmR`

	Technological Maturity	Energy Cost	Location Limitations	Public Opinion	Policies
(A)-CAES	Partially mature	Good for most applications	Most countries can build underground reservoirs (tanks)	Mild opposition expected	Most developed countries are funding R+D projects USA: funding opportunities for storage solutions EU: Germany removed the tariff for storage in the grid MO: unknown
Hydrogen	Large-scale: to be demonstrated	Good for large-scale long-term		Some security concerns	
Flux Batteries	Large-scale: to be demonstrated	Good for small-scale short-term	No specific restrictions	Concerns about chemical spills	
Pumped Hydro	Mature	Competitive depending on location	Limited, but there are suitable locations to be exploited	Huge visual impact	

[green] / [blue] = dis / advantage related to the technology

Figure 1.50. Analysis of large-scale storage solutions. Source: IDAE (*Evolución tecnológica y prospectiva de costes de las EERR*) `http://bit.ly/2nRALmR`

There are many factors that have a direct influence on the possible development of these storage technologies, such as their level of maturity, the associated cost, considerations concerning the security of the installations, etc. Figure 1.50 shows a brief analysis of these factors, considering today's four most promising storage solutions:

CAES (Compressed Air Energy Storage) is based on the storage of compressed air in tanks or similar installations. Energy is therefore stored as mechanical energy (pressurized air) (standard CAES) or heat (A-CAES[1]). This technology is suitable for large-scale installations and two main advantages can be cited: a complete scalability of the storage capacity and a reasonable cost for short-term storage. However, its current efficiency (ratio of stored energy versus output energy) is low (40-55% CAES and 60-70% A-CAES), making this the main goal in terms of research in future years.

In summary, CAES is already a commercial technology with current R+D[2] efforts, useful for large-scale capacity adjustment, but with a low efficiency.

Hydrogen Storage is a technology suitable for long-term energy storage based on electrolysis, thus obtaining both H2 and O2 from water. Afterwards, the H2 will be used to produce electricity or heat via turbines.

Hydrogen storage exhibits the highest energy density among large-scale solutions (e.g. 65 times that of CAES) and is the cheapest solution for long-term energy storage. On the other hand, it needs the deployment of large installations and its current efficiency is low ($\approx 40\%$).

Molten salts are used mainly in CSP installations, were the solar radiation is employed to heat a fluid that will be used to produce electricity with turbines. In order to store heat energy, molten salts tanks can be used as they have the ability to store the heat of the fluid over a long period of time, thus allowing electricity production during the night, for example. Its main advantage lies in the absence of energy conversion before storage, thus giving rise to a good efficiency. On the contrary, this technology is not suitable for de-centralized solutions, as the molten salts might freeze during low-radiation periods.

Molten salts are a mature storage technology (with active R+D) focused mainly on CSP, but whose applications for alternative solutions are currently under analysis.

Pumped hydro is the large-scale storage technology most commonly used today. Its working principle is very simple, as it is based on the transportation of water to a higher reservoir, where that potential energy can be recovered by letting the water run to the base reservoir and activating a turbine located between both sites. It is a high-efficiency technology (80%) but it is restricted by the limited number of locations suitable for building these infrastructures.

Pumped hydro is a mature technology with a high efficiency, but limited in terms of new installations.

The "Almacena" project of the REE will be cited to close this section. This large-scale storage project is based on prismatic-cell Lithium-ion batteries, reaching a total storage capacity of 1MW. You can go to the following link for more information: `http://bit.ly/2BKOSSz`.

Following the detailed introduction to REs provided in previous sections, the final section of this chapter will explore the relationship between renewable energies and telecommunications.

[1] A stands for *adiabatic*.

[2] Research and development.

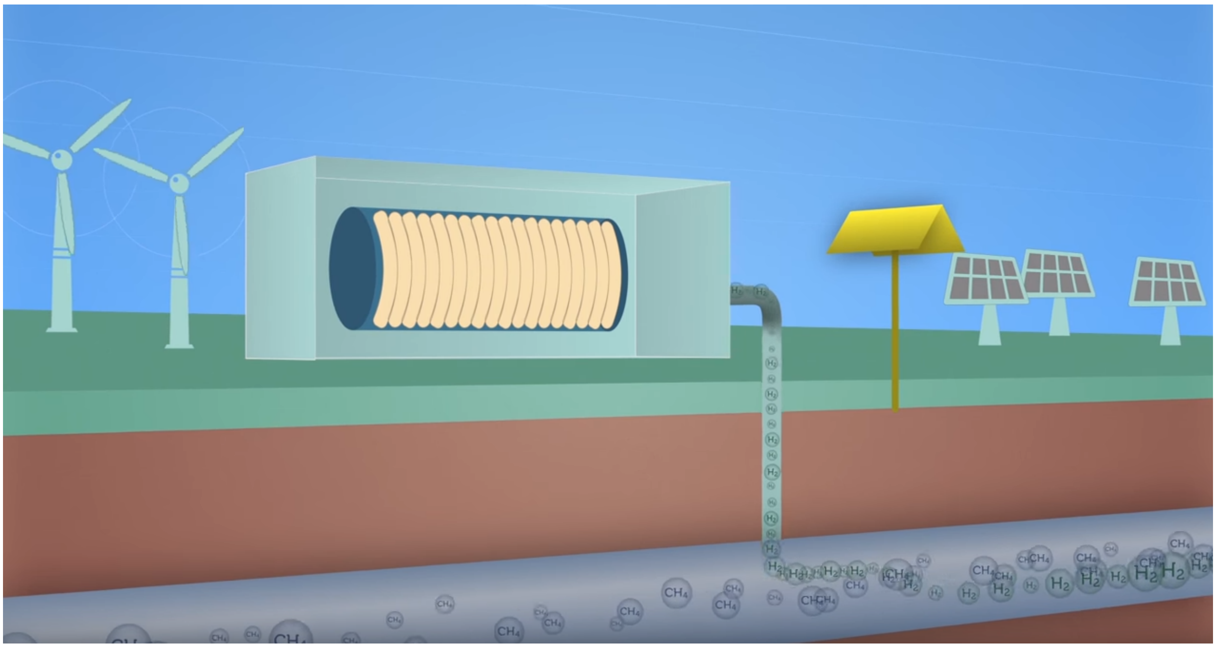

Figure 1.51. Schematic diagram of the storage technology known as “Power to Gas”. Source: YouTube. License: YouTube standard. https://youtu.be/j6ktfz2R9fo

Important! 11.1: Power To Gas

The concept of **Power to Gas** is starting to be relevant over recent years in relation to new large-scale energy storage technologies in the electricity grid.

As explained in the following video, this technology is based on using electrical energy to generate gas, for example hydrogen by electrolysis from water. In this way, the generated gas is easily accumulated and transported by conventional gas pipelines. In addition, this gas can be used to generate energy easily, it could even be combined with CO2 to give rise to other compounds, such as synthetic methane.

If you want to know more about Power to Gas, check out the following video (3 minutes): https://youtu.be/j6ktfz2R9fo.

Question 11.2: Large-scale storage technologies

Only four of the various large-scale storage technologies have been briefly commented on, due to the limitations of the course: look for information on any of the other technologies not discussed here and briefly explain its working principle (**in your own words**).

You can also look for more information about CAES, hydrogen storage, molten salts or pumped-hydro, explaining for example real projects that had been recently deployed or choosing a scientific paper (closely related to this field) to briefly explain its contents[a][b].

[a] Scientific papers are published mainly in English, so you should look for information in this language.

[b] You may consider using scientific databases such as: *Google Scholar* https://scholar.google.es/ or *Engineering Village* http://www.engineeringvillage.com/, among others.

Important! 11.2: Tesla: the biggest Battery in the World

Tesla has recently started to operate a **100 MW/129 MWh battery** in Australia, which has been built in only a few months. The project, whose estimated cost is of around 50 M$, seems to be highly profitable, as it is supposed to have earned more than 1 M$ in just a few days. When supply exceeds demand, consumers are paid to take electricity out of the grid. This battery can do so at a large scale, and it is estimated to earn 790 $ per absorbed MWh, releasing the energy when demand increases. The PowerPack Project is the world's largest lithium-ion battery to date.

Figure 1.52. Tesla PowerPack Project at Hornsdale (Australia). Source: electrek `http://bit.ly/2DJswOW`

Figure 1.53. Elon Musk at the presentation of the Powerpack Project. Source: YouTube (Standard License) `http://bit.ly/2GsLbQP`

1.12. REs and Telecommunications

The close relationships between these two fields will be explored in the following pages, including the most obvious connections (power supply for telecommunication infrastructures) ans less well-known ones: **sensing applications**.

1.12.1. Power supply for Telecommunication systems

The most obvious relationship between REs and Telecommunications is probably the use of the former as power supply for the latter. Small solar PV or even micro or mini wind-power installations can be used to supply power to telecommunication infrastructures. A common example would be a Base Transceiver Station (BTS), as they can be located in places where there is no access to the power grid. These small-scale RE systems might be used to power the whole system or only specific subsystems, such as air-conditioning/refrigeration units[1].

Figure 1.54. Example of a small solar-PV and wind power system associated with a TDT station in Uceda (Guadalajara, Spain). `http://bit.ly/2AZw1ya`

Telecom engineers will readily think of these systems related for mobile phones, TDT, the internet and so on; however, there are other examples also associated with telecommunications but in a completely different scenario: let's see the following example (Figure 1.55).

What can we see in this figure? It is a vehicle gauge system based on magnetic sensors and used as a traffic meter in specific locations, as a step prior to the design of highways, roundabouts, etc. Given that these devices have to be installed in the middle of the road, their power supply via power cables would not be suitable. An alternative solution was proposed based on a **thin-film**[2] **PV cell** like the one shown in the image.

[1] An example of this kind of project is proposed in this TFG: *Diseño de una instalación fotovoltaica para una estación base en Teruel, España* `http://bit.ly/2oMNJo6`

[2] The main solar PV technologies will be studied in the following chapter of the course.

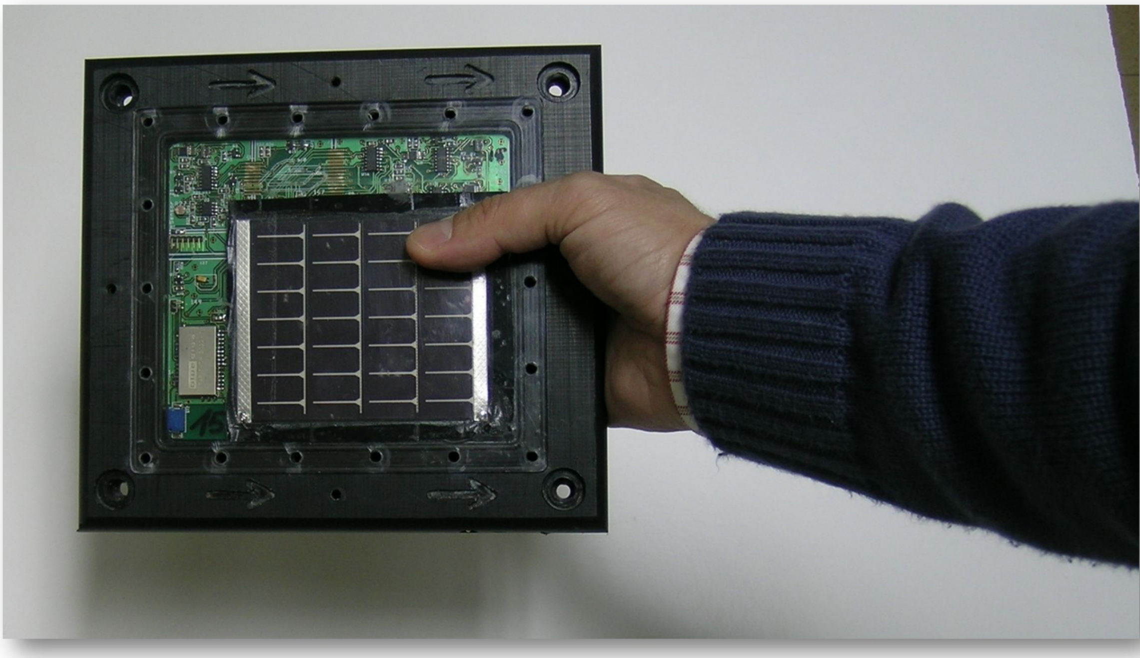

Figure 1.55. Vehicle gauge system developed by the Photonics Engineering Group (Universidad de Cantabria).

1.12.2. R+D

Telecommunications engineers may also contribute to the **research and development of REs**, for example in the **improvement of solar PV cell efficiency**. The photovoltaic laminate, where photon-to-electron conversion takes place, is a silicon P-N junction, although new materials have been explored in recent years. Huge research efforts are being carried out in this field, and also in the associated optics, in an attempt to overcome the 16-18 % efficiency limit.

Additionally, many CSP plants implement sophisticated solar-tracking systems with sensors that measure several parameters like solar radiation or wind speed.

Telecommunications are not only limited to the solar sector: **wind farms**[1] require a **continuous real-time production control and monitoring**. Sensor and communication systems based on optical fiber are used and even wireless solutions have been explored[2].

1.12.3. Sensing applied to REs

The term "sensing" or sensor systems is here referred to systems derived from the telecom arena used to monitor, in real-time if needed, REs installations or plants.

Monitoring of solar PV installations

A typical example is found in solar PV plants, where infrared thermography is used to identify defective PV modules. Infrared cameras allow capturing IR radiation that, as al-

[1] Wind farms refer to wind-power plants formed by several large-scale wind turbines.

[2] This scientific paper proposes a wireless solution based on the ZigBee Protocol: "*Wireless Monitoring of Urban Wind Turbines by ZigBee Protocol: Support Application Software and Sensor Modules*" `http://bit.ly/2D5j88C`

ready discussed in the section on climate change, is associated with a hot body. Hot-spots are a serious problem for PV modules/installations, as they compromise the production of the whole plant. In this manner, at least two thermographic inspections per year of medium/large-scale installations are recommended. Figure 1.56 shows an image of the thermographic inspection of a roof-top PV installation. It can be noticed how there are PV cells, whose temperature is clearly higher than the rest. This is due to the hot-spot problem, which makes these cells operate as loads, thus dissipating heat (and compromising the integrity of the module).

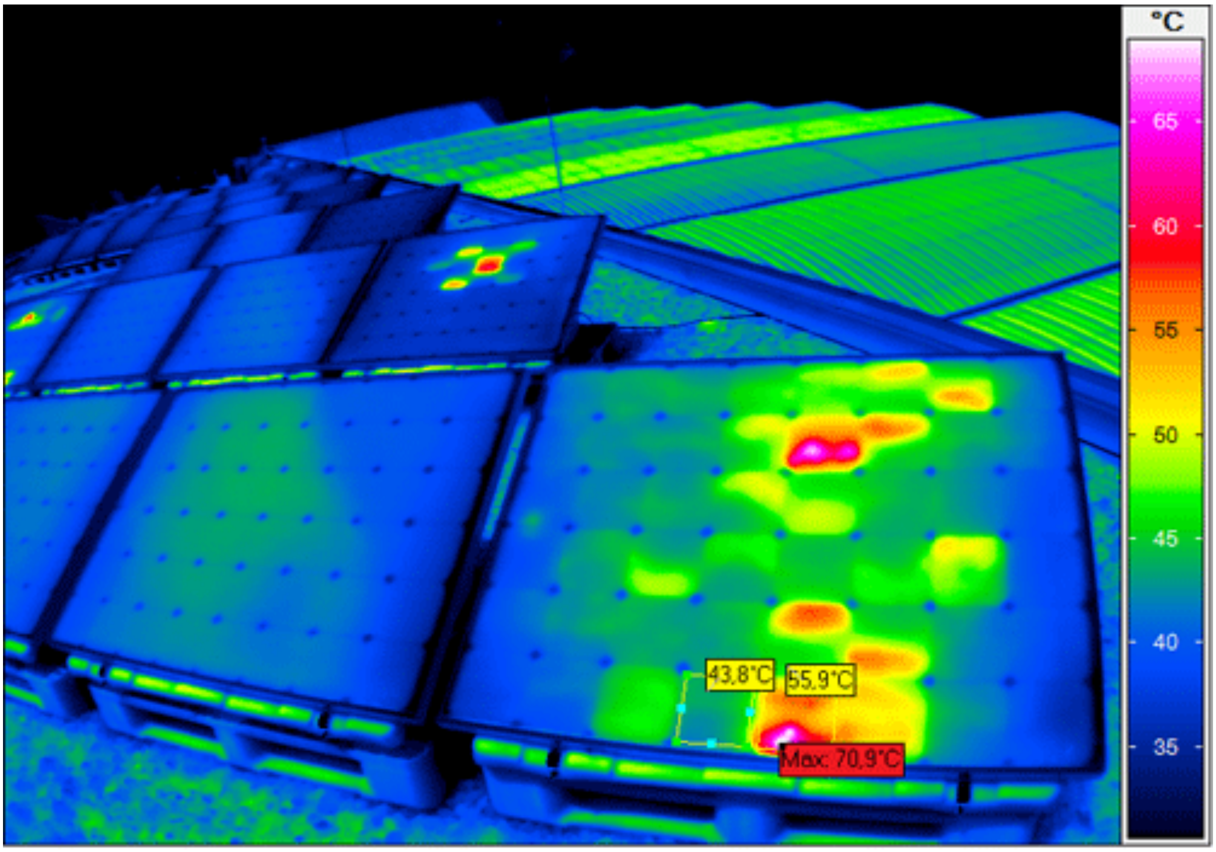

Figure 1.56. Thermographic inspection of a roof-top PV installation. Source: Infratec `http://bit.ly/2CDJIok`

Monitoring of wind power farms: optical fiber sensors

There are many examples of sensing applied to other RE technologies, like wind power. The cost of a large-scale wind turbine might be around 1 to 2 million euros per installed MW, with a cost per blade (European turbines often have three blades) of more than 200.000 euros, depending on dimensions, materials, etc. Of course, ensuring the structural integrity of these elements is of the highest importance, not only to prevent a possible malfunctioning, but also to prevent that situation and take the appropiate measures to avoid a catastrophic situation, like the one recorded in this video: `https://youtu.be/CqEccgR0q-o`.

This video shows how, although the whole structure, including the tower, is destroyed, the situation begins with the breaking of one of the blades, probably because the wind speed was too high and the regulation or braking systems did not work correctly. A

Figure 1.57. Frame of the video where a wind turbine is completely destroyed. Source: YouTube https://youtu.be/CqEccgR0q-o. Standard YouTube License.

question that comes immediately to mind is: what material is a wind turbine blade made of? These blades are made of composite materials like carbon fiber, making the blade flexible. All the blade designs have to be tested in specific facilities to verify their correct behaviour.

The following video shows some of the tests that the blades should undergo to obtain the required certification. This blade is in fact one of the longest ones, measuring 88.4 meters, with a total rotor area of more than three football fields. The deformations of the blade during tests can be clearly seen: https://youtu.be/5m-jwwM3qRs.

Electric gauges (sensors) are typically used in these trials to estimate the deformation suffered by the blade. However, there is fiber-optic technology that allows real-time and distributed (not in a single location, but through the whole fiber length) estimation of blade behaviour. **This is a clear example of a RE monitoring system directly related to telecommunications**. In fact, these sensor systems are easily connected to the wind farm fiber ring communication system, thus allowing a complete integrated solution.

1.12.4. Optical Fiber Sensors: FBGs (Fiber Bragg Gratings)

Fiber Bragg Gratings (FBGs) are point sensors[1] They are able to give information about **temperature** and **mechanical tension** (***strain***) at a specific point in the fiber.

From the physical point of view, an FBG is a periodic variation of the refractive index

[1]"Point" implies that they give the measurement for a specific point, the point of the fiber where the sensor is located.

Figure 1.58. Image of the blade test of a wind turbine blade measuring 88.4 meters long. Source: LM Wind Power. Frame of the YouTube video: https://youtu.be/5m-jwwM3qRs

of the optical fiber core, as shown in **??**. Although there are different types, the operation of conventional FBGs is based on the fact that this element, "written" within the fiber[1], reflects a specific wavelength of the incident light (see bottom of **??**). This wavelength is given by the following equation:

$$\lambda_B = 2 \cdot n_e \cdot \Lambda \tag{1.1}$$

In the previous equation λ_B is the **Bragg wavelength** (which reflects the diffraction network), n_e the **effective refractive index** of the FBG and Λ the **period of the diffraction network** (the separation between the "fringes" recorded in the fiber core). Since the spectral response of the FBG is very narrow (we can be talking about 0.5 or 1 nm), a typical application of these devices is the filtering of optical signals. On the other hand, the Bragg wavelength depends on the temperature and strain to which the fiber is subjected at that point, so they can also be used as sensors of both parameters.

$$\frac{\Delta\lambda_B}{\lambda_B} = C_S \cdot \epsilon + C_T \cdot \Delta T \tag{1.2}$$

In the previous equation we see that both the application of a *strain* (mechanical stress/elongation) to the fiber and a variation in temperature will cause a shift in the Bragg wavelength. Therefore, once it is conveniently calibrated, an FBG can act perfectly

[1] There are different methods of manufacturing FBGs, for example by using phase masks and UV lasers.

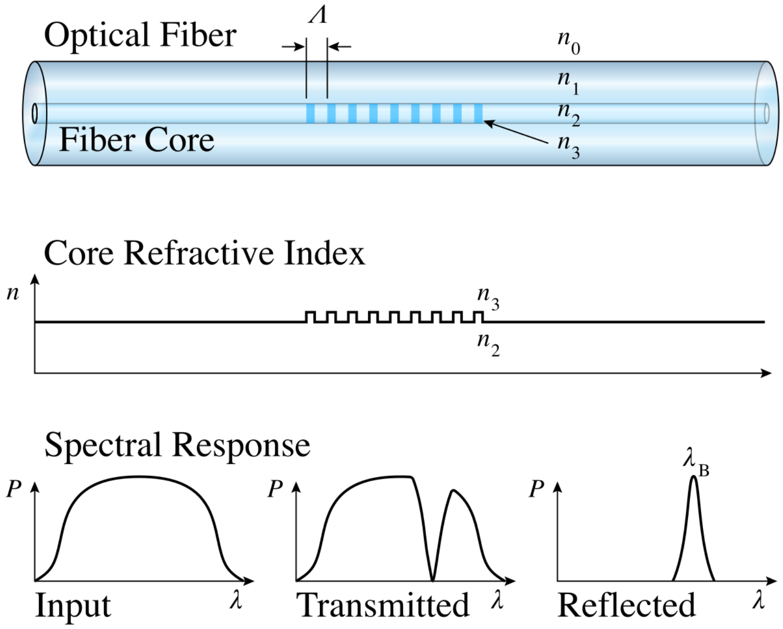

Figure 1.59. Schematic representation of the working principle of an FBG. Source: Wikimedia Commons. License: CC BY-SA 3.0. `http://bit.ly/2JDIjGJ`

as a sensor. Although multiple FBGs can be multiplexed in the same optical fiber using slightly different wavelengths for each one, it is worth noticing that we are talking about a **point sensor**, that is, sensors that measure for a specific point within optical fiber.

Within the multiple applications of FBGs, many are related to renewable energies: from CSP to geothermal power plants, through wind farms, where it may be interesting to monitor from the structural behavior of the wind turbine tower to the rotor blades. In this sense, the **??** shows the installation of fiber optic sensors (specifically FBGs) on a wind turbine blade for later testing and validation.

Important! 12.1: FBGs: Applications (¡BONUS! 800 XP)

FBGs are a mature technology today, with many applications in different fields. Do a search in a specific database (for example Google Scholar: `https://scholar.google.es/`), select a research article about it and briefly explain, in your own words, the application in which these fiber optic sensors are used.

1.12.5. Distributed Optical Fiber Sensors: Brillouin and Raman scattering processes

Optical fiber sensors can also be distributed that is, allow distributed measurements along the optical fiber. This represents great advantages since **large measuring distances (between 100 and 200 km, for example)** can be obtained, **with spatial resolutions of the order of 1 meter**. From a practical point of view this implies that structural structures such as pipelines or power lines can be monitored, with real-time information on what is happening, which would otherwise be very difficult (with other technologies).

Figure 1.60. Fiber-optic sensor installed on a wind turbine blade. Source: Photonics Engineering Group (Universidad de Cantabria)

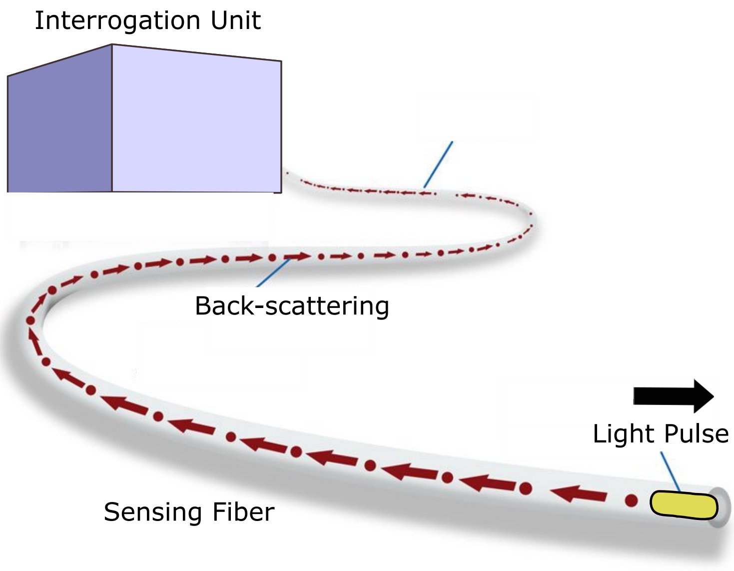

Figure 1.61. Schematic representation of the working principle of distributed optical fiber sensors. Source: YouTube. License: YouTube standard. `https://youtu.be/TQmtv45D50A`.

Distributed fiber optic sensors are based on scattering processes that take place within the optical fiber. As represented in the Figure 1.61, when a light pulse is introduced into the optical fiber, at each point of the fiber the pulse interacts with small “imperfections” or particles, causing a very small fraction of the light associated with the pulse to be “scattered” in the opposite direction to that of propagation. The best known example of the scattering phenomena is probably **Rayleigh** scattering[1], responsible for the blue color of the sky on Earth.

Some dispersion phenomena, such as the so-called **Brillouin and Raman**, are capable of providing very valuable information about the point where the phenomenon occurs. Specifically, the first one allows measuring temperature and *strain*, while the second only temperature. Thus, with a specific interrogation unit (see **??**) and a standard optical fiber, we can have a sensor that provides many measuring points (**more than 1 million!**) along the fiber.

A good example of the application of this telecom sensing technology can be illustrated with the help of **off-shore wind farms**. These “plants” are installed in the sea, normally just a dozen kilometers from the coast, thus avoiding the visual impact of onshore installations. But, how is the energy transmitted to inland locations (where it will be used)? A submarine power cable is needed and, obviously, a problem in this cable could jeopardize the production. How could we detect and locate a problem in this cable?

Question 12.1: Technological Brainstorming

Before reading on, try to find possible solutions that enable the detection and localization of a possible failure in the power cable associated with an off-shore wind power farm. Briefly explain the system and its main features (spatial/temporal resolution, real-time operation, etc.).

[1] For more information about Rayleigh scattering: `http://bit.ly/2YoP1Uo`.

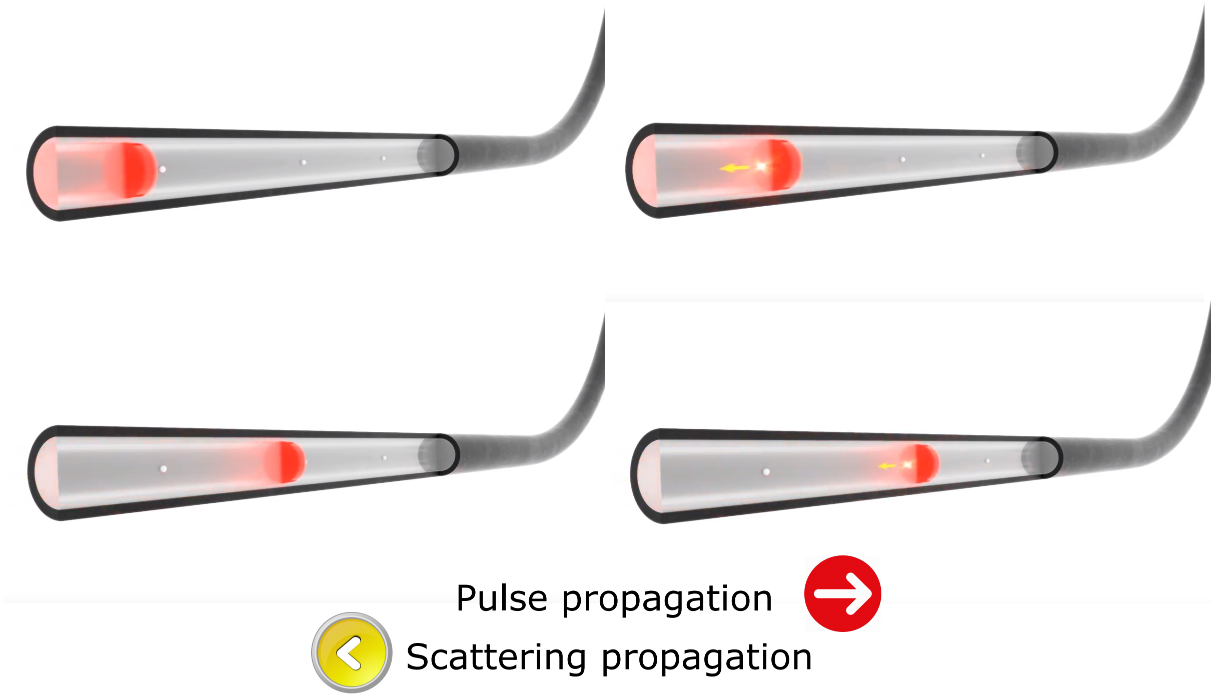

Figure 1.62. Schematic representation of the working principle of distributed optical fiber sensors (interrogation unit). Source: fibergratings.com. `http://bit.ly/2HHCyWu`.

Important! 12.2: Structural Health Monitoring

Structural Health Monitoring (SHM) is a research field not only limited to REs, but mainly focused on civil engineering. These infrastructures are normally very expensive, thus the possibility of obtaining real-time information is fundamental. Bridges, dams, roads, buildings ... there are many examples where SHM could be a key technology.

As an example of the need of using SHM, the following link shows a video of a bridge (part of the AVE railway in Spain) suffering the effect of **resonance**: `https://youtu.be/QTK7siHbAEk`.

It should be mentioned that **resonance**, known for the famous case of the Takoma Bridge[a], is also used as the working principal of a special kind of wind turbine that does not have blades.

Try to find out information about this special wind turbine and briefly explain its working principle in your own words.

[a] `https://youtu.be/3mclp9QmCGs`

Important! 12.3: Low-cost open-source HW: Raspberries, Arduinos ...

Several different platforms, like Raspberry or Arduinos, have evolved over recent years, providing very low-cost hardware solutions enabling the development of interesting solutions. A possibility is to use these system to design monitoring systems related to RE technologies.

An example is presented in the TFG (Trabajo Fin de Grado / End-of-Degree Assignment) of Óscar López: *Sistema de monitorización ambiental basado en hardware open-source alimentado mediante energía fotovoltaica*: `http://bit.ly/2ByCbaW`

A possible solution to this problem could be a **distributed optical-fiber sensor**. These systems are based on scattering effects[1] within the optical fiber: Rayleigh, Raman or Brillouin scatterings. The latter can be used to simultaneously measure temperature and strain[2]. As a defect on a power cable will provoke a heated section, this solution might easily detect and locate the problem.

Question 12.2: Rayleigh scattering

The most common scattering effect is Rayleigh scattering, which is in fact responsible for the blue color of the sky.

Look for information and try to explain **in your own words** how Rayleigh scattering affects incoming solar radiation making the sky look blue.

1.12.6. Dynamic calibration of power lines

As previously commented, one of the main problems of some REs lies in their intermittency: solar and wind power, for example, depend on two sources (solar radiation and wind) that are not constant and may be difficult to predict.

Within this framework, and considering the current impossibility of storing large amounts of energy in the grid, the dimensioning of power lines is an important challenge. The power lines of the grid were dimensioned to cover the needs of the traditional power plants. Nowadays, the different behaviour of modern power plants, such as wind farms, pushes the capacity of these lines to the limit.

How can we tackle this problem? A simple solution would be to replace old power lines with new ones, but the cost of this approach would be huge. A much more elegant and efficient approach lies in the employment of a set of weather sensors to get real-time information about the power line. With this information, it is possible to exceed the nominal capacity of the line (measured in amperes as current (ampacity), given that the tension is constant) if there is a situation reducing the heat of the line: e.g. lack of solar radiation or high winds. In this context, the nominal capacity can be exceeded (as it was statically established for a given temperature) and more energy can be transmitted.

[1] Scattering is an optical phenomenon that takes place when photons meet particles of similar size, being scattered in several directions.

[2] Strain can be understood as the tension suffered by the fiber (longitudinal mechanical tension)

Figure 1.63. Weather sensors being installed in a power line. Source: Departamento de Ingeniería Eléctrica y Energética de la Universidad de Cantabria

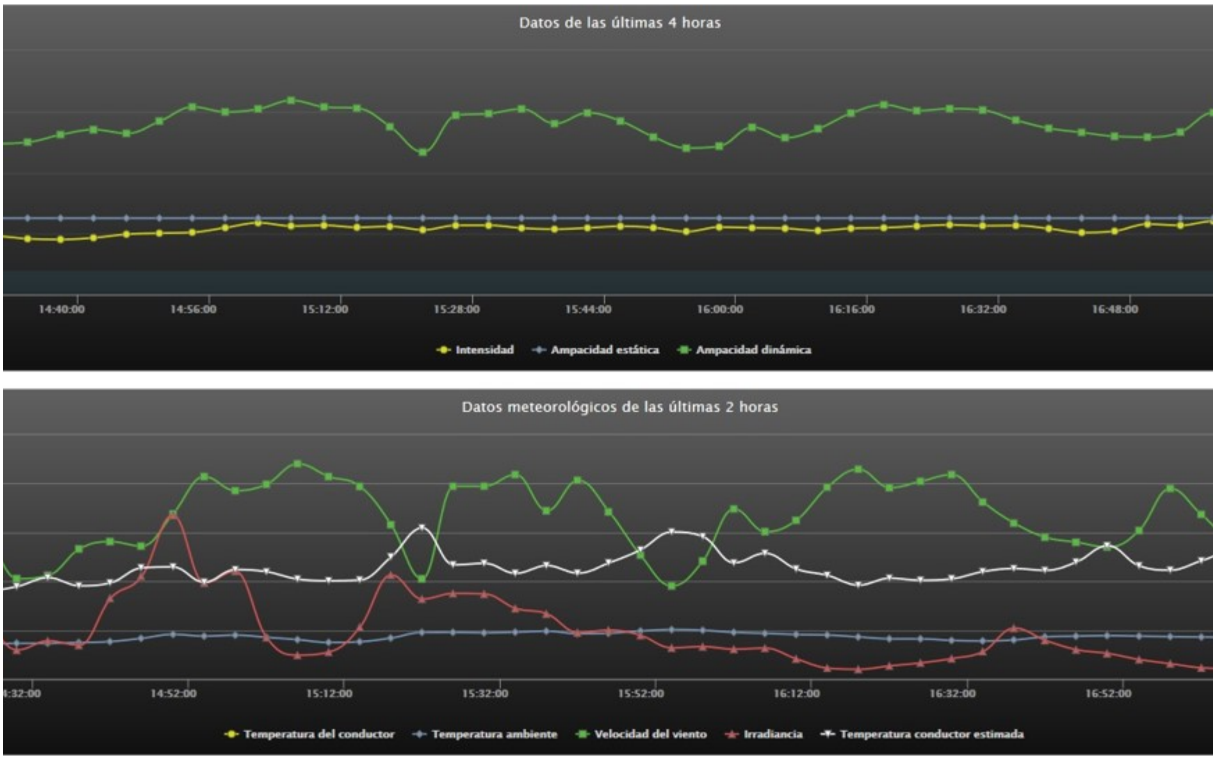

Figure 1.64. Data acquired during the process of dynamic calibration of power lines. Source: Departamento de Ingeniería Eléctrica y Energética de la Universidad de Cantabria

Dynamic ampacity has been represented in Figure 1.64, showing how it can exceed the nominal capacity of the line (top) and how there is a correlation between the wind speed and the cable temperature (bottom).

1.12.7. REs and Telecommunications: Conclusions

As this course has been especially designed for telecommunications students, this section has described some clear relationships between REs and Telecommunications. From the power supply of telecommunications applications, sensor systems or the monitoring of RE installations or R+D efforts, several examples have been provided to allow a better understanding of this fascinating topic.

1.12.8. Introduction to REs: Conclusions

This chapter has been devoted to presenting a **brief approach to REs and to understanding the reasons for their birth and significant evolution in recent years**. Key concepts regarding **climate change** have been discussed. A brief introduction to the **current situation of REs around the world, in Europe and in Spain** has also been considered. The relevance of public **policies on REs** and the key role of **storage solutions** have been presented and, finally, several examples of the close **relationship between REs and telecommunications** have been provided, with a special focus on **telecom sensing solutions based on optical fiber sensors**.

Having completed this introductory chapter explaining the key concepts concerning renewable energies, it is now time to look at two key modern renewable technologies: **solar PV** and **wind power**.

1.13. Appendix: Power Plants in Spain (as of 2020)

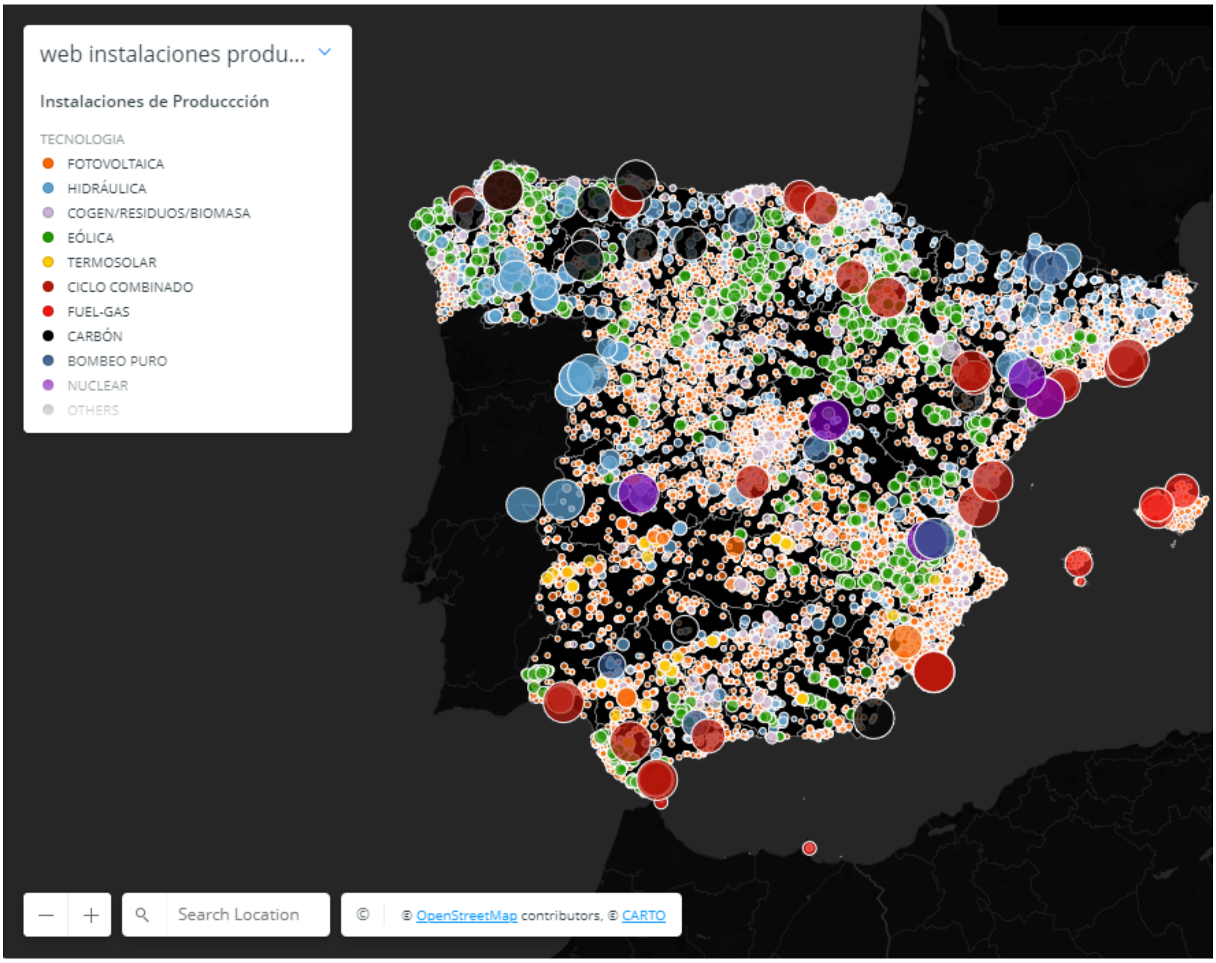

Figure 1.65. Power Plants in Spain (as of 2020). Source: REE. Link: http://bit.ly/30oC8uQ

Figure 1.66. Power Plants in Spain (as of 2020, detail of Canary Islands). Source: REE. Link: http://bit.ly/30oC8uQ

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