Energy Landscape

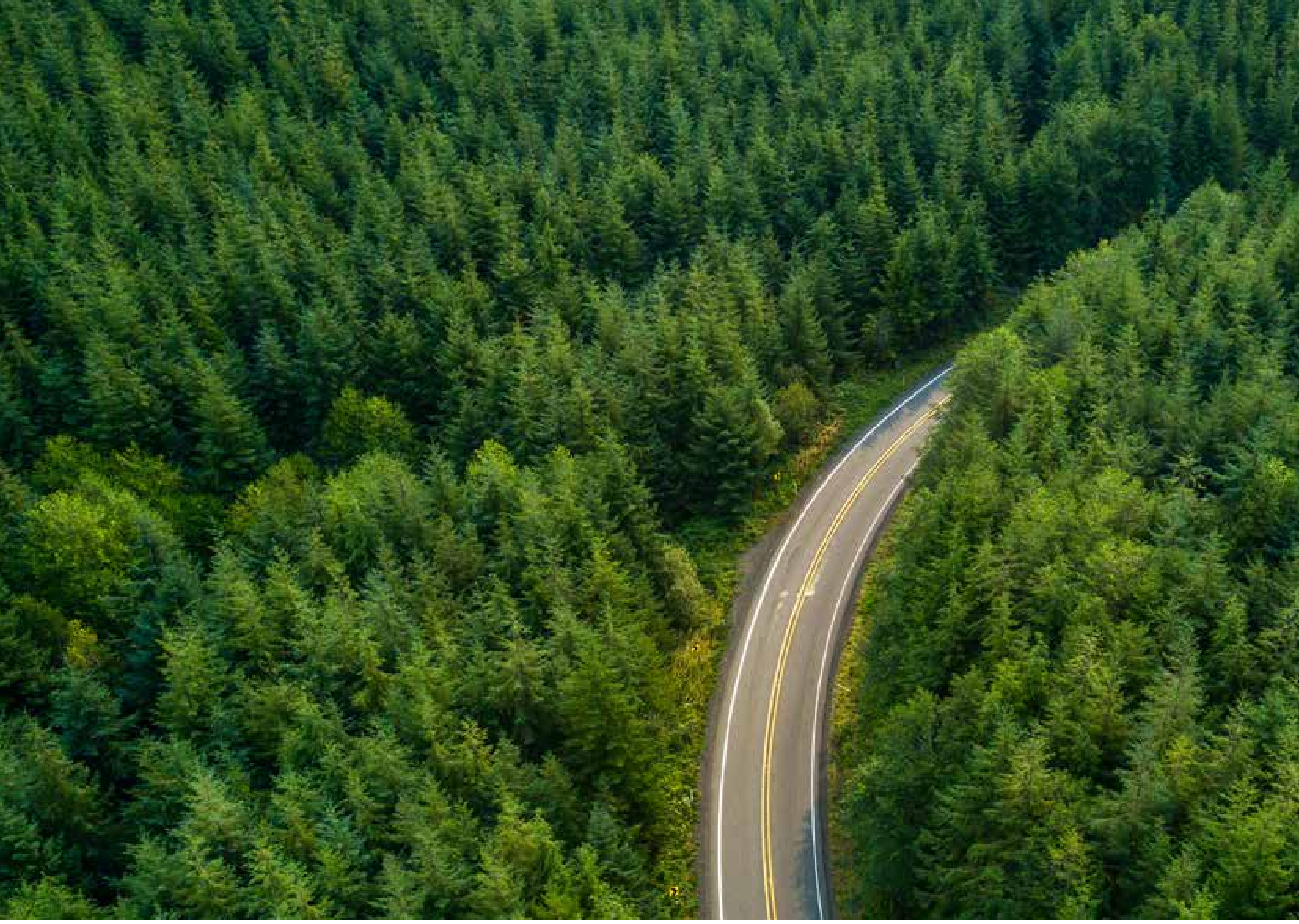
TotalEnergies

In partnership with

Colette Lewiner

and

Capgemini



Introduction

Energy is fundamental to human life and development. Over the centuries, man has learned to harness the Earth's natural elements and use its resources to generate the energy he needs. Initially, biomass (including wood), coal and the sun were used to heat and cook food, and wind and water flow to turn millstones.

From time immemorial, man has been exposed to electricity, notably from lightning; the ancient Greeks had already investigated its properties[1]. This form of energy was only understood and mastered in the 18th century then more extensively in the 19th when it was used for traction in the electric motor, and for long distance communication via the telegraph.

The use of electricity and the development of the steam engine (by which heat could be transformed into mechanical energy) laid the foundations for the industrial revolution. Coal was the fuel that enabled this revolution.

The extraction and refining of oil already used for lighting, began in the 19th century. Oil is used because of its chemical properties and flammability, by which it gives off a considerable amount of heat. It is a highly concentrated form of energy. Natural gas (methane), which was first used at the beginning of the 19th century for public lighting, only came into widespread use in the middle of the 20th century when methane replaced coal gas.

In the middle of the 20th century, spurred by Albert Einstein's scientific discoveries, nuclear electricity became a reality.

[1]Thalès de Milet, around 600 BC.

Largely motivated by environmental considerations, in the 21st century, society is massively rediscovering the "traditional" energies of wind, sun and biomass thanks to their renewable properties.

This brief outline shows that energy is in a state of perpetual transformation with:

- The chemical energy of batteries into electrical and then mechanical energy,
- The chemical energy of oil, gas, or coal into calorific energy then into mechanical energy or electricity,
- The energy potential of waterfalls into mechanical energy or electricity,
- The kinetic energy of wind into mechanical energy and more recently into electricity,
- Solar energy into calorific energy and more recently directly into electricity,
- Nuclear energy into electricity.

Electricity is an elaborate form of energy that can be produced from a variety of primary energy sources (hydro, solar, wind, fossil fuels, uranium) and transformed with very few losses into mechanical energy or heat for consumer use. That is why electricity is referred to as an 'energy carrier'.

The transformation from one form of energy to another can be done without energy cost (conversion efficiency at 100%) or energy loss (conversion efficiency less than 100%).

According to the first principle of thermodynamics, energy is conserved. According to the second principle (Carnot's principle), 100% efficiency in the conversion of heat into mechanical energy or electricity cannot be obtained.[2] The yield varies according to the installation, but the International Energy Agency (IEA) estimated it to be typically 35-40%. The efficiency of conversion of solar photons into electricity is lower (between 7 and 25%).

The characteristics of the various forms of energy vary greatly particularly in terms of:

Storage: Some energies are easily stored, such as fossil fuels (coal, oil, natural gas) and some renewable energies (biomass). These are "preserved" energy sources. The force of water, solar radiation or wind are "renewable energy flows" that must be captured at every moment, only possible if there is wind, flowing water or sunlight. Electricity is still difficult to store.

Availability: Not all of these energies are available when needed. Electricity produced from gas or nuclear power is always available when it is needed, it is referred to as being programmable. On the other hand, wind or solar electricity is only available when the wind is blowing or the sun is shining. These renewable energy flows are intermittent in nature.

The concentrated or diffuse nature of the energy source: Some energy forms are highly concentrated, as in the case of oil, coal, or uranium. Others are diffuse and require much more space for the same amount of generated energy as in the case of solar or wind energy. 1 liter of oil can produce as much energy as 1,000 liters of gas or 50 m^2 of photovoltaic panels at noon for 1 hour, when the sky is clear, and the sun's rays fall perpendicular to the panels.[3]

Cost: Abundant and mature energy sources are cheaper than some rare energies or energies under technical development (fossil energies compared to decarbonated hydrogen for example)

Environmental impact: some negative environmental impacts with varying natures and magnitudes result from energy consumption. This is particularly true for fossil fuels.

Care must be taken when comparing these energies, and in considering all their characteristics, clearly defining what the actual subject is. This point is analyzed in greater detail later in this document.

[2] The conversion of heat into electricity requires a hot source and a cold source. Conversion efficiency depends on the temperature difference between the hot and cold sources.
[3] These characteristics are detailed in chapter 4

Global warming

Anthropogenic global warming is a known fact, recognized by the scientific community, and caused by the accumulation of greenhouse gases (GHG) in the atmosphere.

When generated, carbon dioxide (CO_2), methane, water vapor, or ozone, as well as other gases, accumulate in the atmosphere. They form a layer that allows the sun's rays to reach the earth but prevents the infrared rays emitted by heated elements from leaving the atmosphere. They act like the glass roof of a greenhouse and help to retain heat, from which we derive their name: greenhouse gases (GHG). GHGs have a warming effect on our planet.

During the 20th century and the beginning of the 21st century, the increase in the world population and in the average standard of living resulted in the increased consumption of food, natural plant or mineral resources (vegetal and mineral), and energy.

This led to a sharp increase in GHG emissions contributing to global warming. These have more than doubled in the last 50 years. The consumption of fossil fuels for heating, transportation or electricity production is responsible for more than 80%[4] of the world's CO_2 emissions and for about two thirds of GHG emissions. Global warming requires unprecedented efforts to reduce GHGs without compromising the continued improvement of living standards, particularly in developing countries.

The development of Western countries is largely responsible for the amount of GHGs in the atmosphere. It is now time for these countries to control their emissions, by not generating new ones whenever possible, but also by reducing them or even recovering the emitted carbon using "negative emissions" technologies. Other major emitting countries (China for example) must also reduce their emissions.

Faced with the need for urgent action almost every country in the world has signed the Paris Agreement [5] in 2015. They set themselves the goal of containing global warming to well below 2°C compared to pre-industrial levels, and to continue pursuing actions taken to limit this warming to 1.5°C by aiming for carbon neutrality (balance between anthropogenic emissions and anthropogenic absorptions by carbon sinks) during the second half of the 21st century.

[4] Key figures on climate – 2021 edition – I4CE
[5] https//unfccc.int/processandmeetings/the-paris–agreement/the-paris agreement

This overview of the energy landscapes aims at providing an understanding of the different forms of energy, their origins, and use, characterizing each of them and allowing comparison in full knowledge of the facts, and understanding of the technological progress that has already been made and that is still to come.

This document also provides keys to understanding the climate issues and the progress needed to ensure a supply of energy that is affordable, reliable, and as carbon-free as possible to limit global warming, a challenge that concerns us all. It was produced in partnership with Colette Lewiner and Capgemini.

Table of contents

1

Energy supply

1.1 Basic notions and definitions

VARIOUS TYPES OF ENERGY

Stored in objects, molecules and atoms, energy manifests itself in many ways. In the past, man produced energy from natural elements, either in the form of mechanical energy (wind, waterfalls) to turn mills, or calorific energy (wood to make fire). Eventually, they mastered a wider range of energy sources and defined how these energies interact with each other. Energy comes in different forms: mechanical energy, composed of the kinetic energy of a moving object and the potential energy stored in a stationary object; heat energy, from the agitation of molecules; chemical energy, associated with the bonds between the atoms of a molecule; radiation, nuclear energy stored at the center of an atom; electrical energy, and gravitational energy.

UNITS OF MEASUREMENT

The units of measurement often reflect the original uses of power. Even after the replacement of the horse by steam engines and the automobile, power continued to be expressed in "horsepower".

Fossil fuels have also left their mark on the units of energy measurement used, with petroleum being a key resource in the 20th century economic development. Energy is thus measured in barrels or tonnes of oil equivalent.[6] Annual oil consumption is usually measured in millions of barrels per day.[7]

There are also several reference systems, including the Imperial or US system and the international system, which have different conventions: the same temperature can be expressed in degrees Fahrenheit or Celsius, and we often refer to "cubic feet"[8] of gas rather than cubic meters. These traditional units have been retained because of their practicality and intuitiveness.

Energy

The official unit of the international system (IS) is the joule (J), equal to the work produced by a force of 1 Newton[9] whose point of application moves 1 m in the direction of the force. It is independent of the source of energy considered: 1 J produced from electricity generated by a wind turbine or from the combustion of a gas will heat a specified quantity of water in the same way.

Power

This is the capacity to release energy per unit of time. The joule (J) as a unit of energy, corresponds to the Watt (W), as a unit of power: a power source of 1 Watt used for 1 second releases the energy of 1 joule. 1Ws (Watt second) = 1 J. 1 Kilowatt-hour (kWh) is the energy released in 1 hour by a power source of 1,000 W, equal to 3.6 megajoules (MJ).

[6]A barrel has a volume of 159 liters. By specifying the quality of the oil and its density we can go from tonnes of oil to barrels. In one tonne of oil there are on average 7.3 barrels.
[7]One barrel per day is roughly equivalent to 50 tonnes per year.
[8]1 meter = 3,28 feet .
[9]The newton is the force that is collinear to the motion which, applied for one second to an object of one kilogram, is able to add(or subtract) one meter per second to its speed.

A distinction is often made between the electrical kWh, the energy released during 1 hour by an electrical appliance with a power of 1 kW, and the thermal kWh, which refers to the equivalent quantity of heat.

Commonly used units of energy

Historically, the calorie has long been used to measure quantities of heat. It represents the energy required to raise the temperature of 1 gram of water by 1°C at atmospheric pressure: 1 calorie = 4.187 joules.

An equivalent definition is used in the Imperial and US system, that of the British Thermal Unit or BTU, which represents the amount of heat required to raise the temperature of a one pound[10] mass of water by one degree Fahrenheit, which implies 1 BTU = 251.984 cal.

Derived units

The importance of oil in the energy balance of many countries explains why energy quantities are often expressed in terms of their oil equivalent, which refers to the calorific value of a specified quantity of oil. This is called tonnes of oil equivalent (toe). By convention, it is equivalent to the amount of energy that can be extracted from one tonne of crude oil with a lower calorific value (see below) of 41,868 kilojoules / kg.

The barrel of oil equivalent (boe) is also widely used, especially to add together production or reserves of crude oil and natural gas. It is equivalent to the amount of energy that can be extracted from one barrel (around 159 liters) of crude oil of a specific quality. To compare a barrel (unit of volume) to a tonne of oil (unit of weight), the density[11] of oil must be defined.

For natural gas, we use standard cubic meters (m^3) or standard cubic feet (ft^3) under standard conditions of temperature and pressure[12].

As the basic units defined correspond to small quantities of energy, their multiples are most often used to describe their daily use or in world balances: kilojoule (kJ) for one thousand (10^3) joules, megajoule (MJ) for 1 million (10^6) joules, gigajoule (GJ) for 1 billion (10^9) joules, terajoule (TJ) for one thousand billion (10^{12}) joules, petajoule (PJ) for one million billions (10^{15}) joules, and exajoule (EJ) for one billion billions (10^{18}) joules.

From \ To	Kjoules	kWh	BTU	Teo	M^3	Ft^3
1 Kj =		$2,78 \times 10^{-4}$	0,948	2×10^{-8}	$2,6 \times 10^{-5}$	$0,9 \times 10^{-3}$
1 kWh =	3600		3412	$8,6 \times 10^{-5}$	0,1	0,3
1 BTU =	1,055	$2,93 \times 10^{-3}$		$2,5 \times 10^{-8}$	3×10^{-5}	1×10^{-3}
1 Teo =	$41,868 \times 10^6$	11628	$39,685 \times 10^6$		1136	50×10^3
1 cubic meter =	38×10^3	10,28	$35,069 \times 10^3$	$8,8 \times 10^{-4}$		37,24
1 cubic foot =	1076,1	3	1020	2×10^{-5}	0,027	

Figure 1.1 - Conversion factors for energy and volume
Source : Source: IEA (2021), Key World Energy Statistics 2021 https://www.iea.org/reports/key-world-energy-statistics-2021 All rights reserved.

[10] The pound commonly used today is either the English pound which weighs exactly 453.59237 g, or the metric pound of half a kilogram (exactly 500 grams).
[11] The density of a chemical species is equal to the ratio between its mass and the volume it occupies under standard conditions of temperature and pressure (at 25°C, 1 atmosphere for m3).
[12] Standard conditions of temperature and pressure

CALORIFIC POWER

The energy stored in a combustible material is called the calorific value or heat of combustion.

When gas is burned, the chemical reaction produces water vapor and carbon dioxide (CO_2) and releases a specified amount of heat. The energy that was used to heat the water vapor contained in the gases are vented can be considered as lost. This leads to two concepts for what is referred to as the calorific value:

- **The Gross Heating Value (GHV)**– is an intrinsic property of the fuel. It is defined as the quantity of energy released by the complete combustion of a unit of fuel (a tonne or a m^3 for example), but also the energy released by the latent heat of vaporization of water, which would be recovered if the emitted water vapor were condensed.
- **The Net Heating Value (NHV)**– is also an intrinsic property of the fuel. It is the thermal energy of the fuel that is released by combustion in the form of heat, excluding the energy lost when the water vapor is not recovered (latent heat) at the end of the reaction; it is therefore always lower than the GHV.

The difference between the GHV and the NHV of a boiler is a measure of its efficiency. The lower it is, the higher the efficiency (little energy lost through the vapor). Thus, a condensing boiler based on the principle of recovering part of the energy that would be lost in the steam, has an energy efficiency about 10% higher than a conventional boiler.

THERMAL EFFICIENCY

The production of electricity is based on the Carnot principle. According to this principle, electricity can only be produced from heat with a machine (called a Carnot machine) that has a hot source and a cold source. The efficiency of this conversion (R) is less than 100% and depends on the temperature difference between the two heat sources. The greater this difference, the better the efficiency. It is usually around 33% but can reach more than 60% in combined cycle gas power plants.

So, to produce 1 joule of electricity, 1/R must be used, or about 3 joules of fossil fuels, assuming R=33%. In this example, one joule of electrical energy will be converted into 3 joules[13] of fossil energy. 1/R is therefore the multiplier used for changing from the electric energy used to the fossil energy that allowed it to be generated. It will be referred to as the conversion factor.

The conversion result depends on the value chosen for the efficiency (R), as well as other factors such as the use of higher or lower calorific values. It is also necessary to specify whether the amount of electricity produced is gross or net (i.e., before or after taking line losses into consideration).[14]

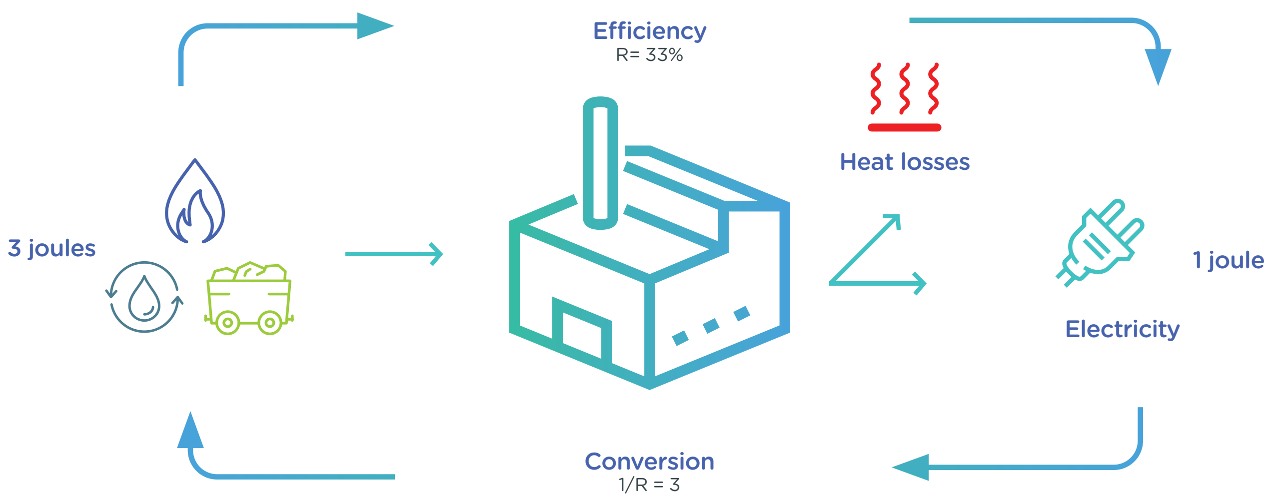


Figure 1.2 : Illustration of the efficiency and heat loss to produce electricity
Source : Capgemini Analysis

[13]This thermal conversion coefficient is equal to 3 for a 33.33% efficiency and to 2.5 for a 40% efficiency.
[14]Gross power generation at the plant level is defined as electricity measured at the outlet of the main transformers. Net electricity production is equal to gross electricity production minus consumption of plant auxiliary services.

1.2 Different forms of energy produced

Energy sources come in different forms, which are described below. Their origin, geographical distribution and exploitation methods vary enormously and, moreover, their share in the world energy mix, their potential, and their impact on GHG emissions is very uneven. A distinction is made between fossil fuels, coal, and hydrocarbons (oil and gas), and low-carbon energies: nuclear and renewable energies (solar, wind, hydro, biomass, and geothermal).

FOSSIL ENERGY

What is it?

Energies from fossil fuels are the most widely used energy sources in the world today. They come in three forms: coal, oil, and gas (the latter two are called hydrocarbons). **Today, they represent the biggest share of the energy consumed in the world with, in 2019, respectively: 162 EJ, 187 EJ and 141 EJ, i.e., about 80% of the world consumption (~607 EJ).**[15]

They are called fossil energies because they derive from the transformation of organic matter under the effect of increased temperature and pressure after being buried under several hundreds to thousands of meters of layers of sediment. This process is millions of years old. The hydrocarbons formed in this buried organic matter in the "bedrock", will migrate toward the surface and eventually be trapped in the reservoir rock where they encounter volumes of porous rock covered by a layer of impermeable sediment. Coal is formed by the transformation of this organic matter into a solid and combustible material with a high carbon content.

Coal is extracted via open-pit or underground mines. The hydrocarbon extraction is mostly carried out by drilling wells on land or at sea at depths that can reach several thousand meters.

Where are the resources?

Fossil resources, because of their generation process, are found where nature has put them. This means that they are unevenly distributed across the planet. Ten countries hold 86% of the world's oil reserves, and ten countries hold a little less than 80% of the world's gas reserves.[17] Coal is an abundant resource found almost everywhere in the world, explaining why it is still so important in today's energy mix, even though ten countries alone[18] hold about 90% of the world's reserves.

[15]IEA (International Energy Agency) (2021) Key World energy Statistics 2021, https://www.iea.org/reports/key-world-energy-statistics-2021/supply All rights reserved.
[16]These countries are, in descending order of reserves: Venezuela, Saudi Arabia, Canada, Iran, Iraq, Russia, Kuwait, the United Arab Emirates, the United States and Libya.
[17]These countries are, in descending order of reserves: Russia, Iran, Qatar, Turkmenistan, the United States, Venezuela, China, the United Arab Emirates, Saudi Arabia and Nigeria.
[18]These countries are, in descending order of reserves: the United States, Russia, Australia, China, India, Indonesia, Germany, Ukraine, Poland and Kazakhstan

	Oil (billions of barrels)		Gas (trillions of cubic meters)		Coal (billions of tonnes)	
North America	238	14%	16	7%	257	24%
South and Central America	293	17%	8	3%	14	1%
Europe	15	1%	5	2%	135	13%
Africa	126	7%	19	8%	15	1%
Middle East	834	49%	81	35%	1	0%
Eurasia	146	9%	77	34%	191	18%
Asia Pacific	151	3%	22	10%	457	43%
World	1702	100%	229	100%	1070	100%

Figure 1.3 : Fossil fuel reserves by region and in the world
Source : IEA (International Energy Agency) (2020) World Energy Outlook 2020, https://www.iea.org/reports/world-energy-outlook-2020

The level of resources is estimated by considering the acceptable cost of their extraction. When this cost is too high, the oil, gas or coal is left in place and will never constitute a viable resource. However, the development of non-conventional hydrocarbons, in which hydrocarbons are extracted directly from the source rock, has brought to light resources that were not previously considered exploitable.

What are the levels of production ?

The quantities of energy produced from fossil fuels on the global scale are significant. **Here are some noteworthy figures:**

Oil

Oil production has increased each year to nearly 100 million barrels per day in 2019.[19] Due to the Covid-19 pandemic and the associated lockdowns, it fell slightly in 2020, for the first time in 10 years.

Thanks to the production of shale oil[20], the United States has become the world's largest oil producer.

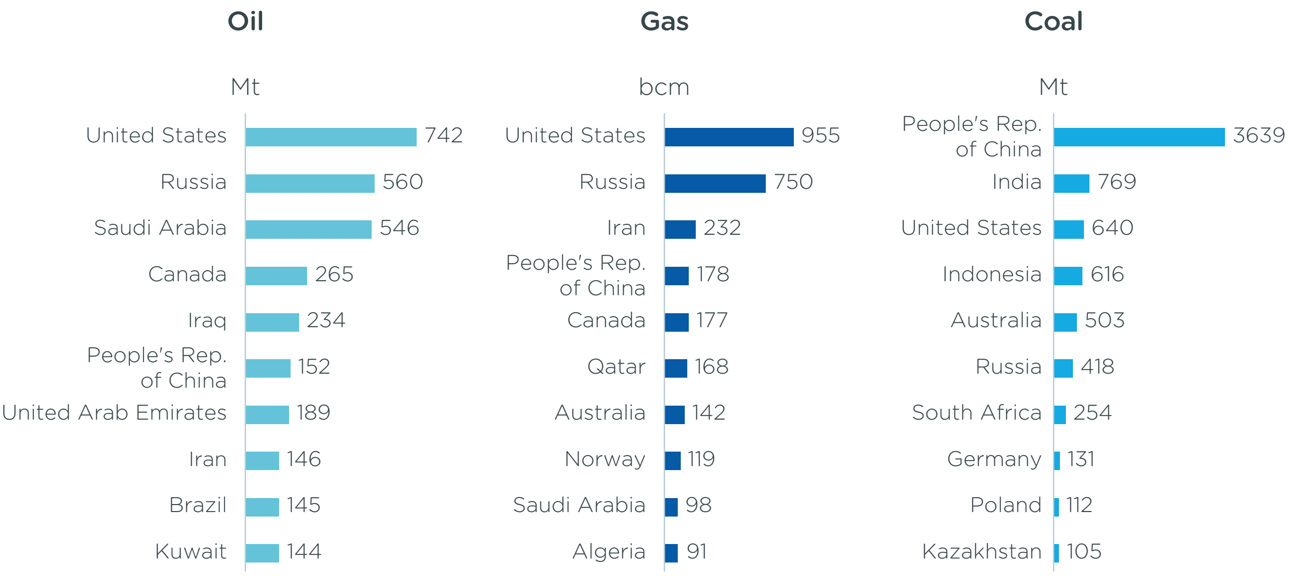


Figure 1.4 : The main oil, coal, and gas producers in the world in 2019 in Mt and billion m³
Source : IEA Key World energy statistics 2020
https://www.iea.org/reports/key-world-energy-statistics-2020.

[19] IEA (2021), Oil 2021, IEA, Paris https://www.iea.org/reports/oil-2021
[20] Light oil from low permeability porous geological formations whose production calls for recourse to hydraulic fracturing method

Natural Gas

In 2019, global natural gas production was more than 4000 billion cubic meters.[21] In the same way as with oil, the discovery and production of shale gas[22] has moved the United States into the slot of being the world's largest gas producer. In the same way as with oil, the pandemic generated a slight decrease in production levels in 2020.

The development of Liquefied Natural Gas (LNG), obtained by cooling gas to very low temperatures (-162°C) so that it can be shipped by sea as a liquid, taking up far less space, has helped make gas a commodity of which large quantities can be transported around the world and traded like oil. However, gas markets continue to be smaller and more specialized than oil markets.

Coal

Worldwide, about 8 billion tonnes of coal were produced in 2019. China, where energy demands are very high, is the world's biggest producer.

Fossil fuels dominate the global energy mix. However, due to long time taken by their geological reconstitution process, **the stock is finite, and is bound to run out in the long term**, more or less quickly depending on how their consumption changes. Due to the loss of pressure during their extraction, hydrocarbon deposits also face a natural decline of about 5% on average per year, which requires regular investment inputs to maintain the same level of production. Moreover, the consumption of fossil fuels emits a substantial amount of GHGs: 14.5 Gt CO_2e for coal, 11.5 Gt CO_2e for oil and 7.3 Gt CO_2e for gas in 2019.[23] **Fossil fuels account for more than 80% of CO_2 emissions and about two thirds of GHG emissions** (see chapter 3).

BIOMASS

What is it ?

Biomass is any organic matter of plant, animal, bacterial or fungal origin that can be transformed into heat, electricity, and biofuels. It is available in solid, liquid, or gaseous forms and was, along with solar energy, the first resource used historically by man. It can be forest residues (wood, sawdust, bark), household or industrial waste, agricultural residues (straw, trees, manure), specific agricultural crops (sugar plants, oil plants) or other types of residues (animal fats), plants dedicated to energy crops (giant miscanthus, switchgrass, biodiesel rape...). **It now represents 10% of the energy consumed in the world.**[24]

How do we use it?

A distinction is made between the use of **traditional solid biomass**, which consists in burning wood, leaves, agricultural waste and manure for domestic heating or cooking purposes in low-efficiency equipment (open fireplaces) and which is a **key resource in many developing countries**, and **modern bioenergy**, which refers to **modern solid biomass** (pellets, chips, logs burned in more efficient closed fireplaces and power plants), liquid **biofuels**, and **biogas**.

Among these biofuels, a distinction is made between conventional (formerly known as first generation) and **advanced** (formerly known as second and third generation) biofuels.

Conventional bio-gasoline is today made from bioethanol essentially produced by the fermentation of sugar (beet, sugar cane) or starch (wheat, corn, potato). In France in 2019, 7.9% of the energy contained in gasoline was of renewable origin.[25]

[21]Source : IEA, World natural gas production by region, 1971-2020, IEA, Paris https://www.iea.org/data-and-statistics/charts/world-natural-gas-production-by-region-1971-2020 All rights reserved.
[22]Gas contained within low permeability porous geological formations whose production calls for recourse to hydraulic fracturing methods.
[23]Source : IEA, World natural gas production by region, 1971-2020, IEA, Paris https://www.iea.org/data-and-statistics/charts/world-natural-gas-production-by-region-1971-2020 All rights reserved.
[24]Source : IEA (International Energy Agency) (2021) Key World energy Statistics 2021, https://www.iea.org/reports/key-world-energy-statistics-2021/supply. All rights reserved.
[25]https://www.ecologie.gouv.fr/biocarburants

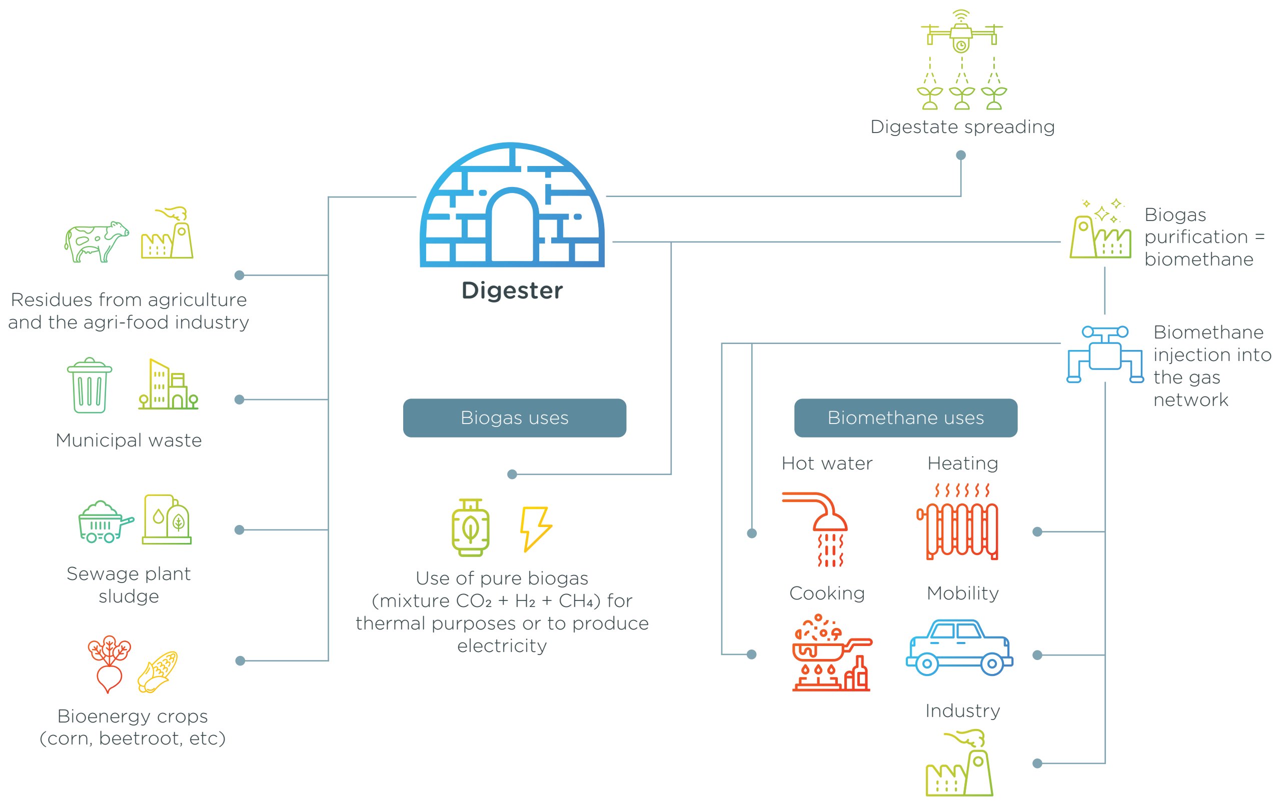


Figure 1.5 : Biogas and biomethane production process
Source : Capgemini Analysis

Biodiesels are produced from oils derived from oil plants (rapeseed, sunflower), animal fats or used oils.

Biogas is produced from the fermentation of organic matter (agricultural and household waste). It can be burned at its place of production to obtain heat and electricity or purified to obtain biomethane that can be injected into the natural gas distribution network.

Advanced biofuels use non-food cellulosic materials (wood, leaves and plant stems) or those derived from waste, and more recently use the oil or hydrogen generating capacities of certain microalgae. This is a promising area of research because these fuels do not compete with the use of farmland for food production.

Where are the resources ?

Biomass is available all over the world in varying quantities. It can be produced locally or imported in large volumes.

Although biofuels have a potential for being produced in many parts of the world, only a few countries have yet decided to produce them industrially: the United States, Canada, Brazil, Argentina, Germany, France, the Netherlands, Italy, Finland, Sweden, China, Indonesia and Thailand.

What are the levels of production ?

Traditional biomass is a source of energy that is regularly left out of energy balances because it is essentially non-commercial and therefore difficult to measure. However, it is estimated that at the beginning of the 21st century, traditional biomass covers about 1 Gtoe per year, or about 10% of the world's primary energy consumption. But locally, and over much of Africa in particular, it represents more than 90% of domestic[26] consumption. In 2018, electricity generated from biomass reached around 635 TWh[27], which is almost double the 2010 production and four times more than in 2000. However, this is only slightly more than 2% of the electricity generated worldwide.

In 2018, two-thirds of the electricity generated from biomass came from solid biomass and the remaining third from liquid and gaseous biomass.

As far as heat production from biomass is concerned, it was about

[26]https://www.planete-energies.com/fr/medias/decryptages/les-differents-usages-du-bois-energie.
[27]Source : IEA - Net Zero by 2050 - A roadmap for the Global Energy Sector
https://iea.blob.core.windows.net/assets/beceb956-0dcf-4d73-89fe-1310e3046d68/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf

800 000 TJ[28] in 2018. According to the IEA, biomass accounted for about 7% of heat production in 2019.

Global biofuel production has increased from 10 Mtoe in 2001 to nearly 95 Mtoe in 2018,[29] an increase of nearly 1000% in 20 years. The United States is the world's leading producer with 40% of global production, followed by Brazil (22%) and Indonesia (5%).[30] By comparison, the global production of petroleum-based "gasoline" and "diesel" fuels will represent roughly 34 billions barrels in 2019.[31]

Using arable land for bioenergy implies competition with the food industry and could cause an unacceptable rise in food prices. Biomass can only considered to be a renewable energy source if its regeneration is at least equal to its consumption.

The biomass renewably generated annually is insufficient on its own to compensate for the use of fossil resources for the world energy consumption.

As far as biogas in concerned, its production generates organic residues called digestates, considered as waste and coming under regulatory production constraints, which vary from one country to another. However, these digestates contain fertilizing materials such as nitrogen, potassium and phosphorus and can be used as fertilizer. Their utilization also comes under severe regulatory constraints, which limits the development of the market.

GEOTHERMAL ENERGY

What is it ?

Geothermal energy uses the underground sources to produce heat, electricity or cold. The heat comes from the Earth's core, largely from the natural radioactive decay of atoms contained in rocks like uranium, thorium, and potassium, with the remainder coming from the residual heat of the Earth's initial formation. It is independent of climatological conditions. It is always available.

Very low-temperature geothermal energy or surface geothermal

[28]IEA (International Energy Agency) (2020) Renewables 2020.
https://iea.blob.core.windows.net/assets/1a24f1fe-c971-4c25-964a-57d0f31eb97b/Renewables_2020-PDF.pdf All Rights reserved.
[29]https://fr.statista.com/statistiques/571267/biocarburants-production-mondiale-2000/
[30]https://fr.statista.com/statistiques/571268/biocarburants-production-dans-les-principaux-pays-par-equivalent-petrole-en/
[31]Source : IEA (International Energy Agency) – World Energy Balance 2020. All rights reserved. https://www.iea.org/fuels-and-technologies/electricity

energy (<30°C) extracted from the first tens of meters, up to 200 m, for individual use with heat pumps. It is sufficient for the heating and cooling of a house, an office building or residential building. It is available almost everywhere.

Deep medium-temperature geothermal energy (30 to 130°) involves finding the resource to a depth of about 2000 m. It can cover the heat needs of urban heating networks or be directly used for industries or farming greenhouses. It is potentially available in many spots on all the continents, but only 12.9 TWh of geothermal heat were produced worldwide in 2019[32] (7.2 TWh in 2010).

Finally, deep high-temperature geothermal energy, from 150° to 300°, capable of generating electricity. Drilling for this energy source is generally to a depth of over 1500 m. It can be modulated but the deposits are limited to the 70 volcanic countries on the "Ring of Fire": Japan-Philippines-Indonesia, the American Cordillera from north to south, the West Indies, Italy, the African Rift. 92 TWh of electricity were produced in 2019 in these countries, less than 2% of the world's electricity produced from renewable energy and about 0.3% of the total amount of electricity generated in the world.

ELECTRICITY

What is it ?

From the beginning of humanity, man has observed electrical phenomena: lightning or the electrical discharge generated by rubbing a cold and dry cloth. The word "electricity" comes from the Greek "electron" which means amber since the ancient Greeks[33] had observed that when amber was rubbed, it would attract very light objects.

Much like water molecules exposed to a gravitational field, electrons[34] flow when they are subjected to an electric field. This electric current is measured in amperes.

The hydraulic analogy for electric voltage or potential difference is the difference in water height in a river. It is measured in Volts.

The hydraulic analogy for the electric voltage or potential difference is the difference in height in a river. It is measured in Volts. The electrical power of a dam depends on the difference in the height of the fall and on the flow of water. The energy content is related to the amount of water stored in the reservoir. In an electrical circuit, the electrical power (measured in Watts) is the product of the potential difference (voltage) and the electric current.

For a dam having a given power level, the energy generated is proportional to the time for which the water flows. In general, electrical energy is proportional to the power and the time during which the electricity is conducted. It is measured in Watt-seconds or with a multiple in kWh[35].

Electricity is transported via electrical grids made of copper or aluminum conductors[36] It is conducted as direct or alternating current.[37]

Because electricity is difficult to store, balance must be maintained constantly between the amount the electricity generated and the consumption. Otherwise the grid will fail and cause a blackout.

Electricity developed as the basis of many uses since the 19th century. It is used for lighting, household appliances and computers, and increasingly for industrial processes and transportation. Subsequently, global electricity consumption in 2018 is more than four times greater than in 1974 (Figure 1.7).

Electricity can be produced from a variety of **primary** energy sources. It is a so-called **secondary energy source or energy carrier.**

What are the levels of production?

In 2019, the worldwide volume of electricity produced was 27,000 TWh, from multiple primary energy sources.

Electricity Of Fossil Origin

Fossil fuels such as coal, gas and oil give off heat and vaporize water as they burn. This water vapor is used to turn a turbine, driving an alternator and producing electricity.

Today, it represents about 63% of the electricity produced in the world.[38]

[32]https://www.iea.org/fuels-and-technologies/renewables#data-browser
[33]Thalès de Millet mentions it 600 years before our times.
[34]The electron is one of the components of the atom (as well as protons and neutrons)
[35]See chapter 4 for the units of measure.
[36]A good electric conductor gives little resistance to the conduction of current.
[37]For DC current, the electrons are always conducted in the same direction. For DC current, the electrons travel alternatingly in both directions of the circuit (they assume a to and fro movement)
[38]IEA (International Energy Agency) – World Energy Balance 2020. All rights reserved. https://www.iea.org/fuels-and-technologies/electricity

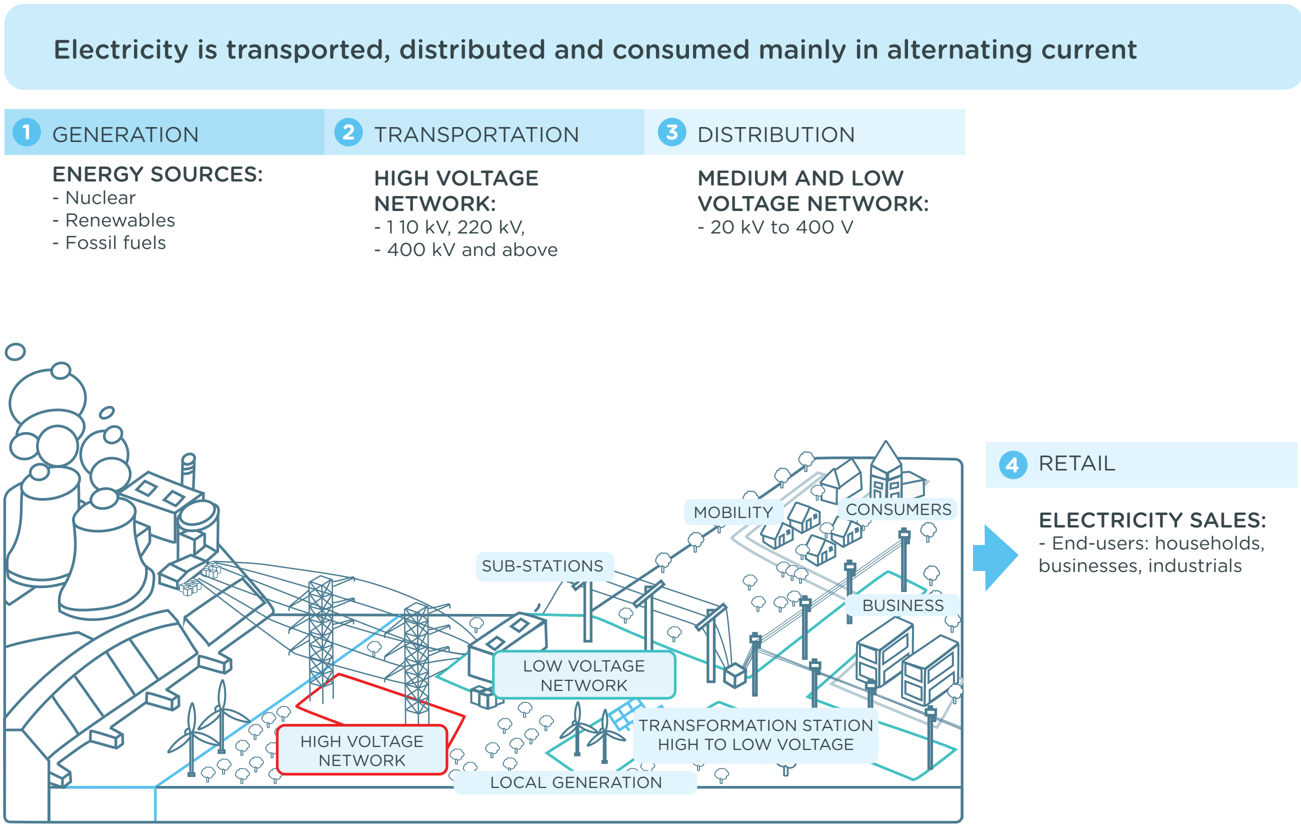


Figure 1.6 : The origin of electricity
Source : EDF

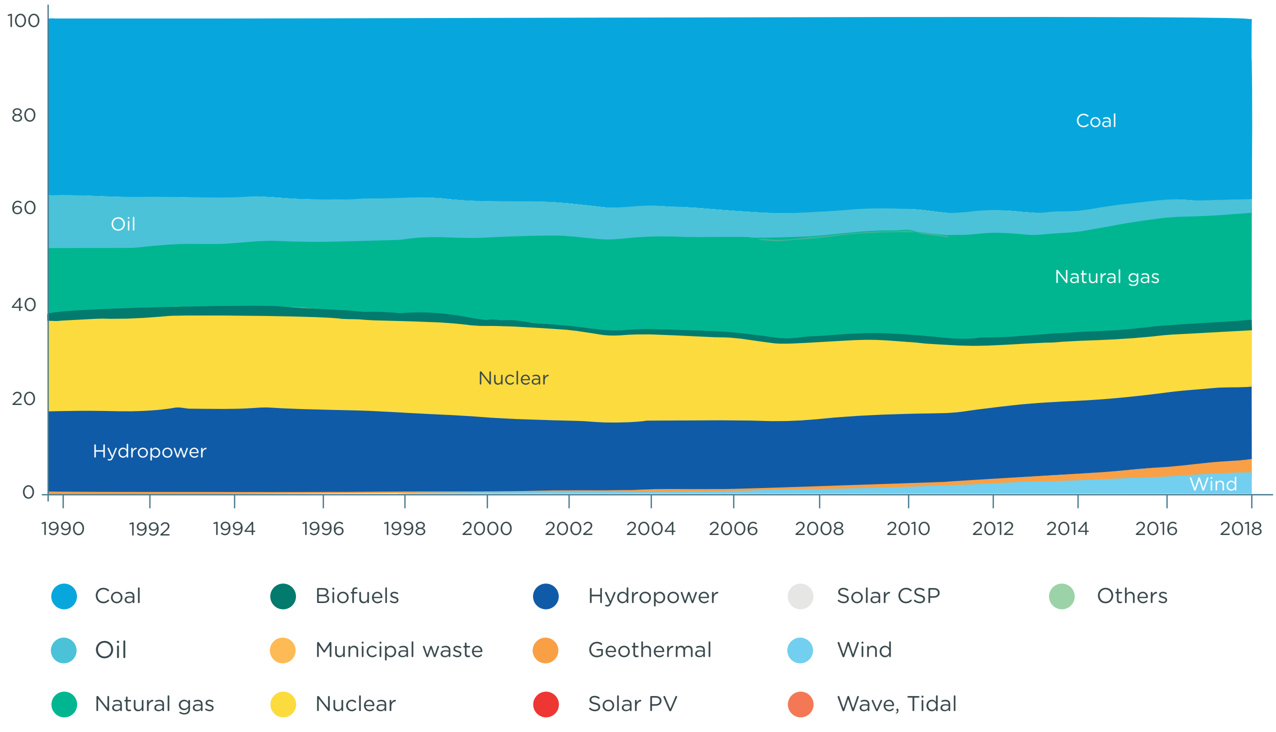


Figure 1.7 : World electricity generation by source (1990 - 2018)
Source : IEA (International Energy Agency) – World Energy Balance 2020. All rights reserved.
https://www.iea.org/fuels-and-technologies/electricity

Nuclear electricity

Nuclear electricity is now produced by nuclear fission, i.e., the splitting of the nucleus of a uranium 235 atom to produce several particles. Since the sum of the masses of the particles produced is less than the mass of the uranium 235 atom, energy is produced according to Einstein's equation $E=MC^2$.[39] As with thermal power plants, the high heat released produces water vapor that turns an alternator.

Uranium is very abundant on the earth and is also found in seawater (albeit in very low concentrations). The vast majority is not economically usable because it is not at a high enough concentration. 10 countries hold nearly 90% of usable Uranium reserves[40] (the biggest being Australia, Kazakhstan, Russia, Canada, Niger, Namibia, South Africa). **It is a non-renewable energy source but is neutral with respect to GHG emissions.** The production of electricity from nuclear energy generates waste having varying degrees of radioactivity and life spans. This waste demands rigorous management with solutions tailored to each degree of danger and that are reliable for the entire duration of its radioactivity.

Today, it represents about 10% of the electricity generated in the world.

Hydroelectricity

Water set in motion, either by a difference in height (power plants backed onto dams or locks), or naturally (run-of-river power plants), drives an alternator turbine to produce electricity. In the first case, potential energy is used; in the second it is kinetic.

Production from conventional dams was 4,305 TWh in 2019 and the theoretical potential is 17,325 TWh.[41] However, its development potential is hampered by the strong impact on movements of the people.

It now represents approximately 16% of the electricity generated in the world.

Wind electricity

Wind energy comes indirectly from solar energy when different places on Earth are heated in different ways. A long time ago, man used this energy generated by windmills to produce flour. The movement of the air causes the blades of the windmill to turn (kinetic energy) and to drive a turbine. The stronger and steadier the wind, the more electricity the wind turbines produce. Modern wind turbines are located out at sea to benefit from better wind resources.

It is estimated that 900 TW of the solar energy received is converted into wind energy, of which a small share is recoverable. At the end of 2020, global installed capacity was 743 GW.[42] UA report from the International Energy Agency (IEA) published in 2019 evokes **a potential of 420,000 TWh per year** in the world. That is **18 times the global demand for electricity.**

Today, it represents about 5% of the electricity produced in the world.

Solar electricity[43]

Solar energy is the energy diffused by the sun's rays, originating from the nuclear fusion reactions taking place in the heart of the sun. There are two technologies for producing electricity from solar energy:

- Photovoltaics uses cells made of semiconductors that emit electrons when exposed to light. This is the most widely used form of solar energy.
- Concentrated thermodynamic solar energy consists in heating a fluid to a very high temperature by concentrating mirrors, and generating electricity via a steam turbine.

Solar energy is also used as a passive and direct means of central-heating and lighting in buildings and of generating heat through thermal sensors which absorb the radiation, using it to heat domestic hot water or central heating systems. It is an inexhaustible energy source, readily available and which does not emit GHGs, found all over the world. **Every 50 minutes, solar energy provides enough power to cover the annual consumption of all the planet's inhabitants.**

It represents about 2% of the world's energy production.

Electricity from biomass and waste

Biomass combustion or waste incineration is used to produce steam and to run alternators generating electricity.

It represents 2% of the world's electricity production, i.e. 637 TWh[44].

[39] C represents the speed of light.
[40] Countries with the largest resources: Australia, Kazakhstan, Russia, Canada, Niger, Namibia, South Africa.
[41] Global resource potential of seasonal pumped hydropower storage for energy and water storage, 2020.
[42] GWEC Global Wind Report 2021 - All rights reserved. https://gwec.net/global-wind-report-2021/
[43] Source : https://www.connaissancedesenergies.org/fiches-pedagogiques-energies
[44] Global Bioenergy Statistics 2020, World Bioenergy Association, http://www.worldbioenergy.org/uploads/201210%20WBA%20GBS%202020.pdf. All rights reserved

Marine electricity

A distinction is made between wave energy, which can be captured by wave technology, energy from marine currents captured by tidal turbines (underwater wind turbines), and tidal energy captured in tidal power plants (a dam built on an estuary allowing flowing and ebbing tides to pass through twice a day) running an underwater turbine. Production currently stands at a low level of only 1 TWh in 2019.

The global potential of tidal energy is estimated as being between 8000 and 80,000 TWh/year. Despite this, only 535MW of power had been installed by the end of 2019. Although this energy source has enormous potential, there is still no way to make economies on a significant scale to reduce the project costs.

It is a renewable, decarbonized energy source, representing about 0.00004% of the electricity produced worldwide.

HYDROGEN

What is it ?

Hydrogen is the smallest atom in the universe, and the lightest. When burned to produce energy, it emits only water vapor. There is hardly any to be found in the natural state on earth and it must be produced from other existing energies. It is referred to as an "energy carrier" in the same way as electricity.

Hydrogen can be used in its liquid (-253°C, 1 bar) and gaseous form at normal pressure, or in its gaseous form compressed at high pressure (300 to 700 bars)[45] and stored using sufficiently strong means.

Hydrogen was found in coal gas networks from the 19th century until the 1970s, when it was withdrawn because of its toxicity, and replaced by natural gas.

Solution for electricity storage

In an electrical system linked to intermittent renewable production facilities, hydrogen can provide a means of storage for up to several days (longer than batteries but shorter than pumped storage) from the excess electricity subsequently restored via a fuel cell (PEMFC Proton Exchange Membrane Fuel Cell at low temperatures and SOFC Solid Oxide Fuel Cell at high temperatures). The hydrogen

[45]Atmospheric pressure (constant) is one bar

produced can also be piped to industrial facilities. In buildings, hydrogen from fuel cells can be used to produce heat and electricity.

Where are the resources ?

Hydrogen is the atom most commonly found on the earth's surface in the form of water (H_20) and organic compounds, but not in its free form. Theoretically, it is available all over the world, but not in the form of directly usable deposits.

What Are The Levels Of Production ?

Today, 76% of industrial hydrogen is produced from natural gas (by steam methane reforming, or SMR process)[46],and 28% from coal[47](ATR process).[48] It is called gray hydrogen which emits large amounts of CO_2 during its production. The 74 million tonnes of hydrogen produced each year in the world generate 630 million tonnes of CO_2, the equivalent of all the world's air transport.

In the same way as for electricity, the challenge is how to produce a decarbonized hydrogen at a competitive price and which is easily available.

There are two ways to produce decarbonized hydrogen:

- The **blue hydrogen pathway** entails decarbonizing the SMR and ATR processes by capturing and storing CO_2. This requires the use of CCS[49],
- The **green hydrogen pathway** entails producing hydrogen by electrolysis from decarbonized electricity, i.e., from renewable sources. This requires progress to be made in terms of electrolyzers (costs, yields)

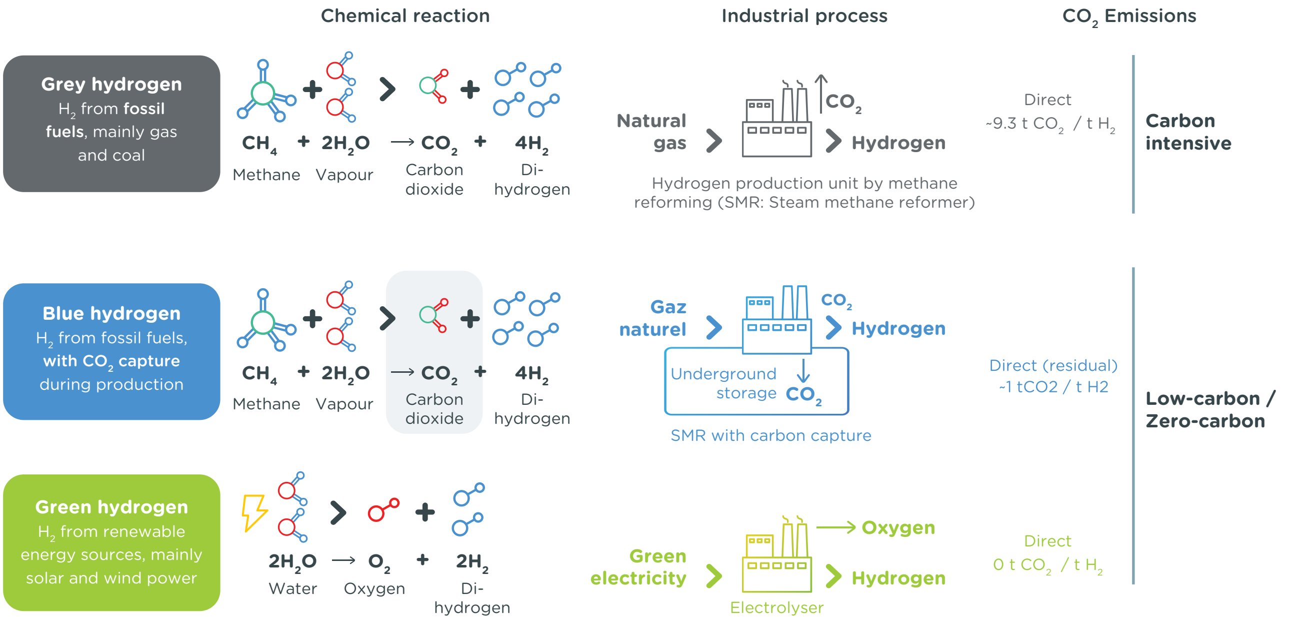


Figure 1.8 : Different types of hydrogen
Source : Capgemini Analysis

[46]Steam Methane Reforming (SMR) : consists in reacting methane with water vapor in the presence of a catalyst. https://www.engineering-airliquide.com/steam-methane-reforming-syngas-production
[47]And ²% by water electrolysis
[48]ATR : autothermal reforming
[49]Carbon dioxide capture and storage device (Carbon Capture and storage

Ensuring the entirety of current hydrogen production (70 million tonnes equivalent to 2,310 TWh according to the IEA) by electrolysis would imply, as an order of magnitude, the equivalent of all the current European electrical capacities. Extensive development of green hydrogen requires the development of very large new surface areas of windfarms or photovoltaic farms at a competitive cost (typically offshore wind or solar photovoltaic resources in desert areas), and the creation of the required transport infrastructures.

Other modes of hydrogen production are also noteworthy: brown and black when the SMR processes use a synthetic gas generated from coal; turquoise, a variant of blue with pyrolysis and CO_2 capture in solid form; pink when the electrolysis is from nuclear electricity; and finally yellow when the electrolysis is from electricity taken directly from the grid.

The renewable hydrogen generated by the use of decarbonized energy can be kept as such or used for the production of e-fuels. In this case, it is combined with a source of CO_2 to produce fuels such as methane, methanol..., or combined with nitrogen to produce ammonia. Depending on the case, these various e-fuels can be used in fuel cells coupled with an electric motor, or in internal combustion engines.

1.3 The major issues of an energy supply

ACCELERATING THE TECHNOLOGICAL MATURITY OF VARIOUS ENERGY SOURCES

The technologies Used to produce energy are not all at the same level of maturity. Changing the energy mix is not only a matter of will but also depends a great deal on the industrial maturity of the technology concerned. This will have a strong impact on its cost and on its capability of being widely rolled out (see graph hereafter).

TRL 8-9

Today

Mature and established technologies

- Hydro, Solar, Wind, Nuclear, Geothermal
- Heat networks
- Heat pumps
- Electric vehicles
- Li-ion batteries
- Solar thermal
- Biofuels
- Biomethane
- Energy efficiency
- Existing heat recovery

TRL 5-7

Before 2030

Technologies in development and emerging on the market

- Marine energy (waves, tidal power)
- Floating wind power
- Small modular reactor (nuclear)
- Autonomous electric vehicles
- Hydrogen for industry and heavy mobility
- Next generation biofuels
- CCS including direct air capture
- Solid state battery
- CSP (Concentrated Solar Power) and 24/7 storage
- Alternative storage (thermal storage, compressed air storage)
- New generation and advanced design energy efficiency

TRL <5

2030-2050

Technologies still in R&D

- Technologies not currently investigated, which will depend on breakthroughs in physics and chemistry
- Zero waste batteries
- Hydrogen airplanes
- New carbon capture technologies
- Fuel or synthetic gas

Figure 1.9 : Overview of low-carbon energy technologies according to their technological maturity
Source : Capgemini Analysis
Note : TRL is a technology maturity index used by NASA "Technology Readiness Level"

IMPROVING EFFICIENCY

Fast technological breakthroughs are happening in the energy industry in both solution efficiency and cost reduction:

The wind industry

Better competitiveness is linked to the use of bigger turbines, better capturing the various wind regimes. Blade weight can be lessened by using composite materials. The load factors of onshore wind turbines are expected to increase from an average of 34% in 2018 to 40% in 2030, and those of offshore wind turbines from 43% in 2018 to over 50% in 2030.[51]

The use of floating platforms also facilitates offshore wind turbine installation and lowers costs (but not during start-up).

The cost of onshore wind electricity has decreased by 8% per year for the past 10 years and the cost of offshore wind should be halved by 2030 according to IRENA.

The solar industry

Over the last 10 years, the industry has taken enormous strides forward thanks to the improved efficiency of photovoltaic cells and the industrialization of their production, leading to a spectacular reduction in average costs of 18% per year.

In the future, lower costs per kWh will come in particular from improved efficiency, due to the research and development of several technologies, such as the "thin film" or heterojunction technologies and perovskite cells.[52]

Fossil fuel power plants

The technological progress of the last few years has improved energy efficiency (expressed by the output) and reduced the energy losses of these power plants. Their efficiency is on average about 35% for coal-fired units and 50% for gas-fired units.

- **Coal**: several technologies can be used to improve power plant efficiency to around 45%: "ultra-

[50]The load factor, given in %, is the ratio between real production and the maximum theoretical production (or the real production divided by the nominal power times 8760 hours).
[51]World Energy Markets Observatory 2020, Capgemini : https://www.capgemini.com/fr-fr/etudes/wemo2020/
[52]https://www.pv-tech.org/oxford-pv-pushes-tandem-shj-perovskite-cell-conversion-efficiency-to-record-29-52/

supercritical" power plants that operate at very high temperatures; coal gasification (Integrated Gasification Combined Cycle) making it easier to combine coal and biomass; and fluidized beds that circulate at lower temperatures (800-900°C), therefore limiting pollutants.

- **Gas**: equipment manufacturers continue to improve turbine design and gas-fired combined cycle power plants are showing efficiency rates of over 60%. To meet the changing electricity markets, gas-fired power plants need to be increasingly responsive to supply electricity, a driving force encouraging the development of aeroderivative turbines that can start up in minutes.

Hydrogen production

Three types of innovation are emerging to improve long term production efficiency:

- The improvement of electrolysis technologies, among which the most proven processes are the alkaline electrolysis and the proton exchange membrane electrolyzer (PEM)[53]. The high temperature solid oxide technology is predicted to bring a significant gain in efficiency[54] but is still at the pilot stage.

- Solar-to-hydrogen (STH) with the capability of producing hydrogen directly from water and light, using panels combining photoelectrodes and electro-catalysts based on nanomaterials.[55]

- The integration of an electrolyzer directly in the turbine of some wind turbines. This method makes for efficiency improvements by eliminating one of the production steps.[56]

[53]Source : IEA (International Energy Agency) – The future of Hydrogen. All rights reserved. https://www.iea.org/reports/the-future-of-hydrogen
[54]Communiqué de presse du CEA « Un rendement de 90 % est atteint sur un système d'électrolyse du CEA » - publié le 4/12/2012
[55]https://www.usinenouvelle.com/editorial/un-electrolyseur-photovoltaique-teste-par-engie-au-crigen.N1008349
[56]https://www.usinenouvelle.com/editorial/idee-verte-produire-de-l-hydrogene-vert-en-mer-au-pied-des-eoliennes.N1049024

IMPROVING STORAGE

Wind and solar power are only available when there is wind or sun. They are by nature intermittent. However, demand and production must be balanced on the electrical grid at all times. To run the electrical grid safely, intermittent renewable energies have to be combined with electricity storage, so that electricity can be supplied even when there is no sun or wind.

- The biggest storage facility is found in two-stage hydraulic dams called PSP[57]. In these dams, water is pumped up from the lowest level to the highest level. It is then stored and can be turbined to generate electricity on demand.
- Essential for the development of electric vehicles but also useful for stationary uses, **electric batteries** that can store a few hours of electricity production have made impressive progress in recent years. The race to build ever-larger factories, on the scale of "gigafactories", has led to spectacular cost reductions. For example, the cost of a Li-ion battery has already dropped by more than 80% between 2012 and 2020.[58]
- Hydrogen is one solution for storing surplus electricity and transporting it to the point of consumption.

Research is continuing to improve battery performance (especially energy density), safety, and to reduce dependency on rare raw materials.

By making large quantities of low-cost storage available, ensuring a rational use of minerals and management of environmental effects, it will be possible to increase the share of intermittent renewable energy sources.

[57]PSP: Pumped Storage Power plant
[58]https://ieefa.org/battery-storage-costs-expected-to-hit-key-cost-reduction-target-by-2023-ihs-markit/

INNOVATING IN NUCLEAR

Research in this field focuses on several stakes. The aim is to improve reactor safety by integrating feedback from past accidents, boosting operating safety, and reducing radioactive waste. Other research focuses on smaller, modular, and therefore more flexible reactors.

The large generation 3 reactors (1000 to 1600 MW) of the EPR (Evolutionary Power Reactor) type offer improved safety. Their large size means that they benefit from scale effects. However, they are difficult to build and this is having a negative impact on their competitiveness.

In recent years, there has been more interest in Small Modular Reactors (SMRs). These SMRs are expected to have improved safety performance thanks to passive safety features. They demand a lower initial investment and should be easier to build. However, they take up a much larger surface area per unit of electricity produced and do not benefit from scale effects.

In the future, these two types of reactors should coexist.

Mastering the technology of the fusion reaction rather than the fission reaction to produce electricity would represent the greatest innovation in nuclear energy. It is the goal set for the international ITER (International Thermonuclear Experimental Reactor) project, which brings together 35 countries, most of them nuclear powers, but it is not expected to reach completion before 2050.

EXPLOITING DIGITAL SOLUTIONS FOR OPTIMIZING PRODUCTION AND CONSUMPTION

Technological advances are speeding up thanks to the use of data and digital tools.

Here are some examples applied to the power grid:

- Electricity grids carrying not only electrons but also increasing amounts of information enabling operators to better balance consumption (demand) with production supply, especially with the growing share of intermittence. Reference is made to (more) intelligent grids (Smart Grid) with tools linked to consumption (smart meters).
- Digital twins[59] make it easier to build and operate power plants, (and especially maintain them) - a digital model of a production facility allows testing and keeps ahead of issues to reduce the risk of failure, find solutions and thereby, improve yields.
- Automation of the control of fossil fuel power plants cuts maintenance costs.
- Sensors connected to wind turbines tell us more about the wind and how to make the most of it.
- More granular and accurate weather forecasts, using artificial intelligence, improve wind and solar power generation forecasting.
- Drones monitoring power lines ensure faster and better detection of failure points.

[59]A digital twin is a digital replica of the equipment in the power station and operating equipment.

1.4 Conclusion

Mankind has always needed energy to ensure its subsistence and development and always sought the most efficient energies to achieve this. Confirmation of this comes essentially by the quest to find available, affordable, and reliable energy and, for several years now, sustainable energy, i.e. the least carbon intensive possible. It is difficult to combine all these factors and trade-offs are essential.

Mankind has developed new energy carriers from the existing energy sources offered by nature. The main sources of energy are not only fossil fuels and uranium, but also the sun, the wind, water movements, geothermal energy, and biomass. Not only have they enabled mankind to survive but also to significantly improve their living conditions.

Currently, 80% of the world's energy comes from fossil fuels, which are high greenhouse gas emitters. To reach carbon neutrality, deep-reaching changes will be necessary in the decades to come to produce energy that is less carbon intensive. Other changes will also be needed in consumption habits to move towards less carbon-intensive energy and improved energy efficiency. These topics will be examined in the following chapters.

2

Energy demand

Since the 18th century, mankind has experienced tremendous improvements in living standards thanks to the abundant use of fossil fuels, but such improvements have been offset by the increase amount of GHG emissions in the atmosphere.

If energy is to remain reliable, affordable and accessible to all, while mitigating the impact of climate change on the planet, we need to diversify energy sources and move towards new modes of consumption in an attempt to massively reduce GHG emissions. Mankind is moving from an industrial society heavily dependent on fossil fuels toward a more varied set of energy sources that are more complementary to the planet, but which require a closer match between energy and uses, and between supply and demand.

In a much more multifaceted energy system, each type of energy use will need to be associated optimally with each type of energy source, including how a given energy is transported to the end user.

2.1
Which types of energy for which uses?

TYPES OF ENERGY ACCORDING TO THEIR DEGREE OF TRANSFORMATION AND THEIR PRACTICALITY

The energy we use undergoes several transformations. Energy is therefore commonly categorized into primary energy, secondary energy and energy carriers, final energy, and useful energy.

It is generally necessary[60] to transport these energies to the end user via land or sea, by building networks of varying complexity (oil pipelines, gas pipelines, heat and cold networks or electricity networks) completed by other logistical means (trucks, trains, ships...). Therefore, today's energy system is based on a vast array of infrastructures and equipment whose development is one of the challenges to be tackled in the energy transition. Energy storage comes with varying levels of complexity, and involves a number of constraints. In particular, the difficulty of storing electricity makes running electrical grids complex due to the need for constant balance between electricity demand and production.

Primary energy

Primary energy is **untransformed energy** as found in nature upon its extraction: coal, oil, gas, biomass, heat from the earth, wind, movement of water, radiation from the sun.

Primary energies can be used and sold without transformation (coal, gas, biomass) or with a minor transformation keeping the same liquid or gaseous form and generating a maximum of 10% to 20% losses (fuels and combustibles from oil, gaseous fuels).

Energy carriers

On the other hand, energy carriers correspond to energy sources that have been profoundly transformed in their nature. The main carriers are electricity, heating and cooling networks, and soon, hydrogen and synthetic fuels and gases. They are produced from primary energy sources in one or more stages. The number of these stages is a key factor (costs, yields).

[60]Except in the case of very local use such as biomass, solar used for domestic hot water, and photovoltaic solar, which can be produced and used locally

Carriers are useful for at least three reasons. Once the infrastructure has been built, they are easier to transport and market as final energy. They are relatively standardized and, thus, easier to use in the equipment that generates the energy we use (heaters, motors, lamps, electronics, vehicles). Finally, they improve the flexibility of a country's energy system by allowing several primary energy sources to be used.

Energy carriers have an important disadvantage: in this transformation process, significant quantities of energy are lost, especially as heat, which is generally not reused.

Final energy

This is the energy that is sold and distributed to end customers. Final energy is sold in four main sectors: residential, commercial, industrial, and transportation.

Useful energy

This is the portion of final energy which is actually available to the consumer after final conversion for its respective use (boilers, heat pumps, lighting, stoves, industrial equipment, engines, vehicles...). The need for an additional stage of transformation to serve the needs of the consumer also induces energy losses in the form of heat.

The useful energy consumption equals the primary energy production less all the transformation and transport losses along the distribution chain and at the customer's premises.

One example could be an incandescent lamp powered by a gas power plant. The plant efficiency is 33%, and the loss during grid transport is 5%, meaning that the consumer only gets 95% of the transported energy. When the lamp is used, 35% of that energy will be used to produce light, while the remaining 65% just produces unwanted heat. The total lighting efficiency is therefore 33% x 95% x 35% = 10%. Nine tenths of the primary energy have been lost in the process.

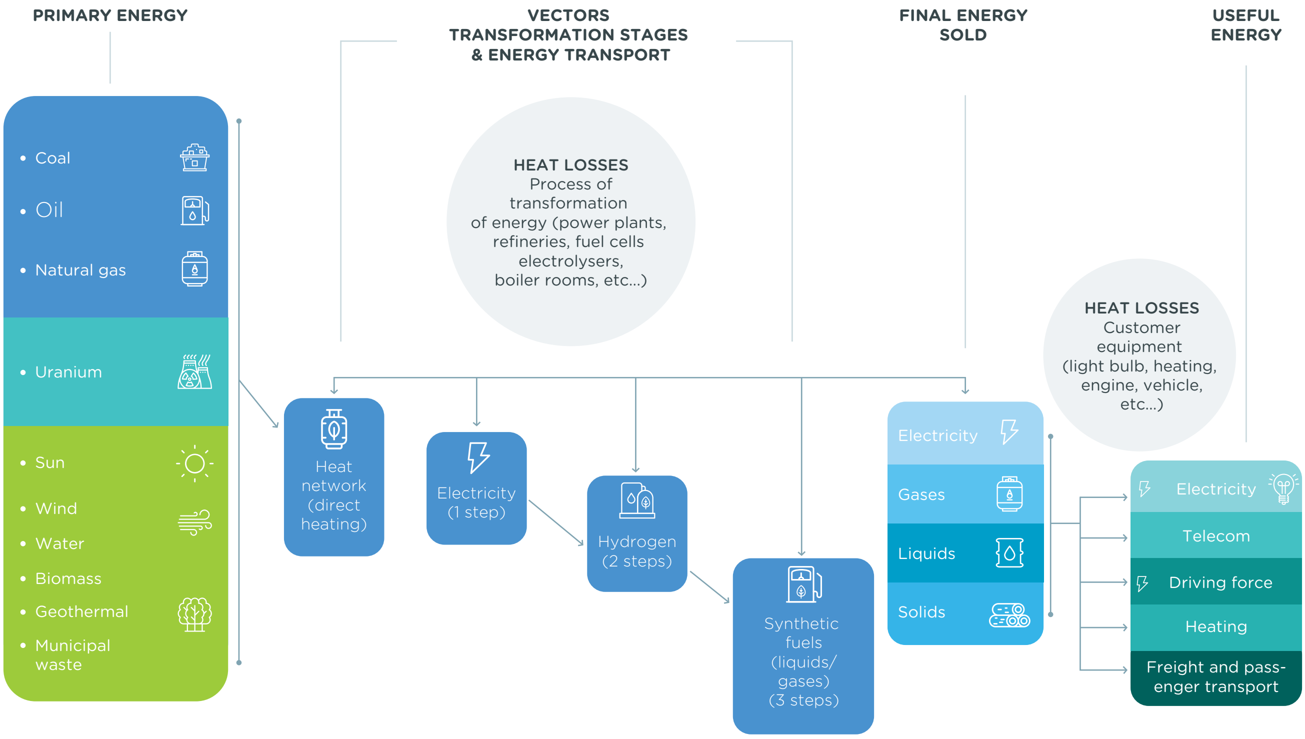


Figure 2.1 : Energy transformation steps and associated losses
Source : Capgemini Analysis

THE LOGISTICS OF TRANSPORT, DISTRIBUTION, AND STORAGE OF ENERGY

This section presents the pros and cons of the various forms of energy with respect to transportation, distribution to end users, and storage.

Solid forms

Solid forms are primary energies not requiring transformation, e.g. coal, solid biomass like wood and straw. They can be stored and transported efficiently on platforms or in large capacity containers.

Typical modes of transport are:

- High-capacity transport on an international or national scale or to large industrial sites: bulk shipping, trains.
- Local distribution to the final customer: road by trucks.

Liquid forms

Liquid forms have the most energy density per unit in terms of volume. They are the most easily stored forms of energy: in tanks of various sizes, as well as in mobile tanks for vehicles. Liquids are easily transferred by gravity or by pumping from one mode of transport or storage to another.

Typical modes of transport are:

- International and domestic distribution to large customers: ships (tankers), pipelines, trains, or trucks,
- Local distribution to end users: road by tanker.

Electrical form

Electricity requires infrastructure offering the advantage of transporting and distributing energy continuously, cleanly, and silently from the power plant to the last appliance at the customer's home: the electricity grid. Electricity has many uses, some of which are specific (lighting, all digital devices).

It is easily transported over distances of up to several thousand kilometers as alternating current[61]. Underground or underwater means are mainly used in the case of direct current. As things now stand, the maximum distances are a few hundred kilometers, but they will increase. Electricity is difficult to store and the quantities are small compared to the volumes required. Solutions include: hydraulic pumping stations (very efficient), expensive batteries with limited capacity, transformation into hydrogen, but efficiency is very low (see Chapter 1).

End-to-end transmission of electricity includes:

- High-capacity transmission on an international or national scale or to large industrial sites: high-voltage transmission grid (several hundred thousand volts).
- Local distribution to the end customer: medium-voltage distribution grid (several tens of

[61]https://www.totalenergies.fr/particuliers/parlons-energie/dossiers-energie/comprendre-le-marche-de-l-energie/comprendre-la-difference-entre-courant-alternatif-et-courant-continu

thousands of volts), then low-voltage grid and electrical circuits at the customer's premises (380 volts, 220 volts, 110 volts depending on the region and usage), as well as telephone and IT telecommunications networks.

Heat or cold form

Heat or cold are transported as heated water (or steam) or cooled water networks over short distances, like a city, a district, or an industrial zone

Gases (sometimes liquid at certain stages of their transformation)

The main gas energy forms include purified natural gas, petroleum gases such as propane and butane, biogas, biomethane, and hydrogen.

The fact that gas is transported by pipeline makes it a convenient network energy, like electricity. However, gases represent a risk due to their explosive nature in case of leakage and mixing with oxygen in the air within a closed area, but stringent equipment and safety standards mitigate this issue.

The low energy density in terms of volumes of gases requires them to be densified, by compression or cooling, all the more so as the gases get lighter, for transport by sea or overland or in bottles.

Gases have an intermediate storability, falling between that of liquids and electricity. Natural gas can be stored for several months in porous geological structures during the summer to cover peak winter

demands for heating, or in bottles and tanks at consumers' homes.

Typical gas transportation modes are:

- International and national high-capacity transport or to large customers: transport ships such as LNG (liquefied natural gas at temperatures of -162°C), pipelines, national gas transport networks (several tens of times the atmospheric pressure or "bars").
- Local distribution to the end customer: local distribution network (a few bars) then to the meter then piped to the customer's stove or boiler; trains and tankers (liquid or high pressure); gas bottles transported by road (liquid or high pressure).

A gas pipeline takes up the same land easement as a high-voltage power line but carries five to ten times more power for the same price. For this reason, it is better to manufacture hydrogen where renewable energy is abundant and transport it by pipeline, rather than transporting electricity to produce hydrogen in the country of consumption.

The cost of transporting energy: infrastructure and logistics

Electricity, oil, gas, heat or cold require large upfront investments in the transmission and distribution networks and logistics described above.

Solid forms require investments in ships, ports, trains, and storage areas - liquid forms may also require investments in pipelines. The last few kilometers transported by road include the logistical costs of trucks and labor, but also the hidden costs of road infrastructure.

Energy trading patterns vary greatly: 70% of oil consumption worldwide is traded internationally, unlike gas and coal, where the volume of international trade is still low, at around 30% and 20% respectively.

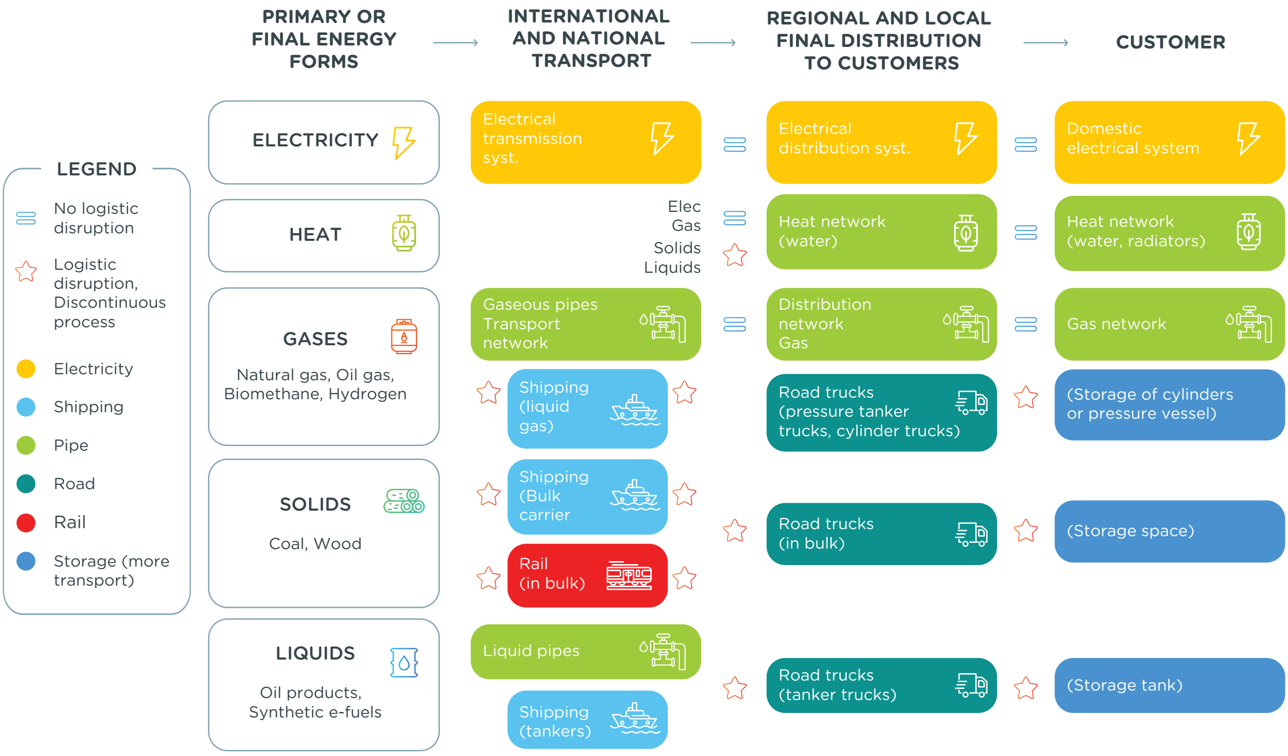


Figure 2.2 : Transport and logistical breakdowns of the different forms of energy
Source : Capgemini Analysis

TYPES OF USE AND THEIR ENERGY SOLUTIONS

Five sectors use energy for their own purposes: residential, tertiary, industrial, transport, and energy production.

Their uses are linked to their needs. We have chosen a way of segmenting them, offering a distinction between the types of energy absolutely necessary to meet a need.

It is also a way of visualizing for which uses it is better to reserve certain energies that are expensive to produce and require long transport chains, degrading the yield. The text and the summary table list the uses and solutions that we believe will be most commonly considered by 2030.

Heat (High temperature)

Industrial processes call for temperatures of several hundred to several thousand degrees to produce metals, glass, and other materials and to transform them (furnaces), but the same applies to the food industry and the residential sector for roasting by radiation (cooking of meats).

The forms of energy currently used include fuels that produce flames from 1200°C to 1500°C, whether fossil or from biomass or recycling, as well as electricity with arcs or electric plasma torches.

The solutions that can be envisaged today, or that could be practicable in about ten years to decarbonize this use, include:

- **A strong reduction of emissions:** CO_2 capture associated with fossil combustion or use of syngas[62]
- **No emissions:** decarbonized electricity, decarbonized hydrogen that produces a flame at 2045°C
- **Net negative emissions:** CO_2 capture associated with the use of biomass or biogas

CO_2 capture and sequestration is feasible for large industrial facilities. Using liquid synthetic fuels is not necessarily advisable. The production of these fuels is quite consuming in economic terms and with respect to the required resources and energy. They are better used as fuels for transport, where it is difficult to use fuels that are not liquids.

[62]See Chapter 3

Heat (low temperature)

It takes several tens of degrees to hundreds of degrees typically to heat buildings and domestic hot water, but also to dry or boil... in the residential, tertiary, and industrial sectors.

The energy forms currently used are almost the same as for high temperature heat, to which can be added the heat networks traditionally supplied from fossil fuels.

The solutions that can be envisaged today, or that could be considered in the next ten years or so, to decarbonize this use are: decarbonized electricity with heat pumps, biomass, biomethane, biogas, heat networks produced from decarbonized and recovered energies (waste, recycling of low-temperature heat output from high-temperature industrial processes).

Cooling

Cooling is useful for reducing heat in residential and tertiary buildings, in the distribution of perishable goods, and in industry. Individual or centralized cooling equipment (air conditioners, reversible heat pumps, chillers) essentially consume electricity and discharge heat locally. The solutions that can be envisaged today, or in the next ten years or so, to decarbonize these processes are decarbonizing, cooling networks using efficient cooling units or cooling directly from rivers or the subsoil, etc.

Uses specific to electricity

These are:

- Lighting, digital uses (computers, telephones, screens), tele-communications.
- Rotating machines and motors used in the residential, tertiary (household appliances, elevators) and industrial (machining, assembly, conveying, ventilation...) sectors. Electric motors are so practical that they render unlikely a return to the direct use of wind or water (mills), or regrowth of internal combustion engines using fossil fuels being used almost exclusively for transport.

These uses are are considered specific because the use of electricity is indispensable. GHG emission reductions related to these uses can be made by decarbonizing electricity.

Mobility of people and transport of freight

In transportation, the two key segmentation criteria are the mode (road, rail, river or sea, air) and the duration of the journey, which requires a greater or lesser amount of energy to be transported in a viable form depending on which mode is selected. If we refer to the duration of transport rather than the distance in kilometers, it becomes possible to compare several modes of transport and several energies.

This is primarily relevant for local freight and passenger transport, within urban areas.

SECTOR	USAGES		CLASS-ICAL SOLIDS coal biomass	CLASS-ICAL LIQUIDS eg gasoil gasoline biofuels	CLASS-ICAL GAS natural gas & others, biogas methane	Electri-city	District Heating & Cooling	Hydro-gen	e-Gas-es, carbo-nated (*)	e-Liqu-ids, carbo-nated (*)	e-Liqu-ids, ammo-nia & others	CCS
IND, ENER	**Heat, high temperature-** several hundred to thousand degrees.	**Industrial processes (transformation materials, metals, glass...) and power generation**	xxx	xxx	xxx	xxx		xxx	xxx			xxx
RES, TERT, IND	**Heat, low temperature -** several dozens to hundred degrees.	**Heating building drying, buildings and Industry**	xxx	xxx	xxx	xxx	xxx	x	xxx			
RES, TERT, IND	**Cold**					xxx	x					
RES, TERT, IND	**Specific usages** of electricity	**Light-Digital-Communications**				xxx						
RES, TERT, IND	**Motors & moving force -** stationary	**Washing machines lifts... (residential, commercial). Industrial tools, convey-ing, ventilation, compressed air... (Industrial)**				xxx						
TRAN	**Road-** short duration 1 to 4 hours	**Freight and passengers, local**		xxx	xxx	xxx						
TRAN	**Road-** middle duration up to 1 day	**Freight and passengers, local and International**		xxx	xxx			xxx				
TRAN	**Rail-** middle duration up to 1 day	**Freight and passengers**		xxx		xxx		xxx				
TRAN	**River and maritime-** short duration up to 4 hours	**Ferries**		xxx		xxx						
TRAN	**River and maritime-** middle duration up to 1 to 2 days	**Ferries et River freight transportation**		xxx				xxx				
TRAN	**Maritime-** long duration up to several dozens days	**International maritime freight**		xxx	xxx					xxx	xxx	xxx
TRAN	**Air-** short duration	**Passengers and high-value freight-national**		xxx				xxx				
TRAN	**Air -** long duration up to 12 hours	**Passengers and high-value freight-inter-continental**		xxx						xxx	xxx	

Legend :
IND = Industry
TRAN = Transportation
RES = Residential
TERT = Tertiary
ENER = Energy production

Available today

Probably available in the decade

Figure 2.3 : Table of uses, sectors, final energies, and CO_2 capture currently and by 2030
Source : Analyse Capgemini

Short distance road transport (one to four hours)

The current solution is based on liquid fossil fuels from oil and gas used in combustion engines for commercial vehicles, vans, buses, and cars.

The solutions that can be considered today, or that could be considered in the next ten years or so, to decarbonize this process are:

- Partial reduction of CO_2 emissions: liquid and gaseous fossil fuels with improved performance of combustion engines, reduction of vehicle size and weight, bio/agricultural fuels or biomethane.
- Zero emissions: electric motorization with batteries powered by decarbonized electricity, or with fuel cells powered by renewable hydrogen.
- Zero emissions and fewer natural resources required, for the short distance transportation of individuals: a switch from the individual electric car to the shared electric car and to the light two-seater and individual electric transport modes.

At present, hydrogen is less suitable than electricity for cars that are used for short periods of time due to issues of economic profitability, but it can be relevant for commercial vehicles that may require a greater range.

Using liquid synthetic fuels is not necessarily advisable. The production of these fuels is quite consuming in economic terms and with respect to the required resources and energy. It is better to use them as fuels for transport that cannot do without fuel in liquid forms, such as air and international maritime transport.

Medium distance road transport (up to a day)

This typically concerns the transport of freight (trucks) and passengers (buses, cars) on a national and international scale. It can also concern vehicles used intensively all day in urban areas (buses, delivery trucks, dump trucks, taxis, etc.)

The solutions to decarbonize this use are the same as those mentioned above, but with stronger competition between electricity and green hydrogen, which allows storage and use over a longer period of time and distance, especially for freight transport and heavy goods vehicles. A hydrogen vehicle has a hydrogen tank, a fuel cell that transforms hydrogen into electricity, and an electric motor like in electric vehicles.

Rail transport – medium distance (up to a day)

This concerns both passenger and freight trains. Some trains are electric, especially in densely populated countries. But eelectrifying railways is expensive. This is why some rail transport still uses diesel locomotives, especially in Europe.[63]

The use of biofuels as a transitional energy, electrification, and the switch to hydrogen (decarbonized hydrogen tank and fuel cell that produces electricity for the electric motor) are the main solutions being considered to decarbonize rail transport.

[63]Source : IEA (International Energy Agency) – The future of Rail. All rights reserved. https://www.iea.org/reports/the-future-of-rail

River and maritime transport – short and medium distance (up to one or two days)

These are mainly short and medium distance ferries and freight transport along rivers that use liquid petroleum fuels in combustion engines.

Possible solutions to decarbonize these uses are based on the use of bio-LNG, liquid bio/agricultural fuels, electricity, and the switch to hydrogen.

Maritime transport - long distance (up to several weeks)

This concerns international maritime freight between continents, which uses liquid petroleum fuels in internal combustion engines.

The solutions that can be envisaged today, or in a timeframe of about ten years, to decarbonize this process:

- **20% reduction of GHG emissions:** switch to liquefied natural gas (LNG). LNG is currently being used more and more, although it requires tanks that are twice as large. LNG limits sulfur emissions.
- **50% reduction of GHG emissions:** carbon-based synthetic fuels[64].
- **High reduction of emissions:** carbon capture directly on the boats with conventional fossil fuels, agro/biofuel. BioNGL immediately improves the greenhouse gas emissions balance.
- **No emissions (carbon neutral):** non-carbon liquid e-fuels such as ammonia[65] (but which take up twice as much space as LNG and four times as much space as petroleum fuel, and are toxic).
- **Negative emissions (carbon negative):** efficient agricultural/biofuels with carbon capture performed directly on the boats.

Hydrogen is not suitable for this type of long-haul transport. A liquefied hydrogen tank must be 2.5 times larger than an LNG tank, which is equivalent to adding 40 meters in length to large international LNG container ships. It is also 7 times larger than a conventional oil fuel tank.

[64] Synthetic carbonaceous e-fuels are produced from green hydrogen associated with captured CO_2, for example at the exit of a coal-fired power plant. Where there were 2 uses that emitted CO_2 (the power plant, the transport that burns the fossil fuel in its engine), there is now only 1 use that emits CO_2 to the atmosphere (the transport that burns the synthetic fuel in its engine while emitting CO_2), that is to say a global reduction of 50%.
[65] Non-carbon e-fuels such as ammonia are produced by combining green hydrogen not with CO_2 but with nitrogen. The engine burning the fuel emits only water and nitrogen. The emission reduction is 100%.

Air transport – short distance

High-value passenger and cargo air transport - domestic or close international. Air transport uses liquid petroleum fuels, kerosene for jet propulsion and aviation gasoline for propeller engines.

The need to carry a lot of energy in a small volume prevents the use of battery-powered electricity today, except for specific cases of light aircraft over short distances.

Possible solutions to decarbonize air transport:

- Agro/biofuels
- Synthetic liquid carbonaceous e-fuels (halving of emissions).
- Liquid hydrogen is also being considered, although it would take four times the volume to carry the same energy as a liquid petroleum fuel, with an adapted aircraft design.
- Electricity: considered in some countries for domestic routes (example: Norway’s coastlines).

Air transport – long distance (up to twelve hours)

Air transport on long transcontinental routes must carry large volumes of fuel. For these reasons, the only possible solutions are liquid fuels with a high energy density per unit volume (biofuels and carbon-based e-fuels).

2.2 Energy consumption

SECURITY OF ENERGY SUPPLY

Energy is essential to human activity and to the well-being of people. Countries have to ensure the security of their energy supply, a requirement that is often at the forefront of public policy. This is the issue of energy sovereignty.

The past has taught us that energy supply and geopolitics are often linked.[67] The concentration of oil resources in the Middle East, the creation of the OPEC (Organization of the Petroleum Exporting Countries) cartel and the embargo decreed by the latter in 1973 during the Yom Kippur war led to the first energy crisis.[68]

[67]Geopolitics and energy Colette Lewiner E-Book WEMO 2020 www.capgemini
[68]https://www.connaissancedesenergies.org/fiche-pedagogique/choc-petrolier

It was following this energy crisis that policies to improve energy efficiency[69] and diversify energy sources were put in place. To improve its energy independence, France launched a major program of nuclear power plant construction.

The production of shale oil and gas[70] has allowed the United States to become the world's largest producer of oil and gas and thus ensure its energy independence.

In January 2009[71], following one of the many conflicts between Russia and Ukraine, Europe was deprived of Russian gas for several weeks and some countries that depended heavily on this supply (Greece, Bulgaria, Balkan countries) were deprived of heating at the peak of winter. Further, the depletion of the North Sea gas fields[72] has weakened European independence. But at the same time, thanks to the opening up to competition initiated by the European Commission, there are now more LNG import terminals on the European coasts. These terminals have made it possible to diversify gas supplies and have reduced fears in terms of the energy security fallout from another geopolitical rift.[73]

The development of renewable energies is driven both by the desire to limit GHG emissions (see Chapter 3) and by the impressive drop in their cost. Since their "fuel" (sun and wind) is universally shared, geopolitical tensions related to energy are easing, but there is a risk being passed on to the supply of strategic raw materials for the manufacturing of equipment to harness energy from these renewable sources. Solar panels, wind turbines and batteries are essentially imported (China, Asia) and contain rare earth elements[74]. These are mainly extracted in China or refined in China (such as lithium, cobalt or graphene) creating a dependence on this country in particular.

In 2017, Europe launched a strategic plan, the "European Battery Alliance"[75] to repatriate part of this battery production and ensure a certain level of energy sovereignty.

[69] With better energy efficiency, energy consumption is reduced for the same service
[70] https://www.connaissancedesenergies.org/fiche-pedagogique/gaz-de-schiste
[71] https://www.cairn.info/revue-geoeconomie-2014-4-page-95.htm
[72] https://totalenergies.com/media/news/press-releases/uk-total-announces-new-discovery-north-sea
[73] Invasion of Crimea by Russia in 2014
[74] Rare Earth Elements belong to the list of 30 materials listed by the European Commission as “Critical Raw Materials”.
[75] European Battery Alliance (EBA 250). https://www.eba250.com/about-eba250/

GLOBAL ENERGY CONSUMPTION IS INCREASING

The growth of the world's population and its standard of living have led to a constant increase in energy consumption since the industrial revolution. The energy efficiency efforts implemented in the OECD over the last 50 years have not been sufficient to significantly slow down this trend.

To determine the level of energy consumption, we aggregate the primary energy consumption of all countries, all sectors combined.[76] In 2019, global energy consumption reached 606 EJ[77], up 0.7% from 2018.[78]

The year 2019 is a better reference for the analysis of medium-term trends than 2020, which was an unusual year because of the pandemic's impact on the global economy. This included a period of near-global lockdowns in the spring of 2020, during which energy consumption fell by about 20%.

Today, 81.3% of the energy consumed is still produced from fossil fuels.

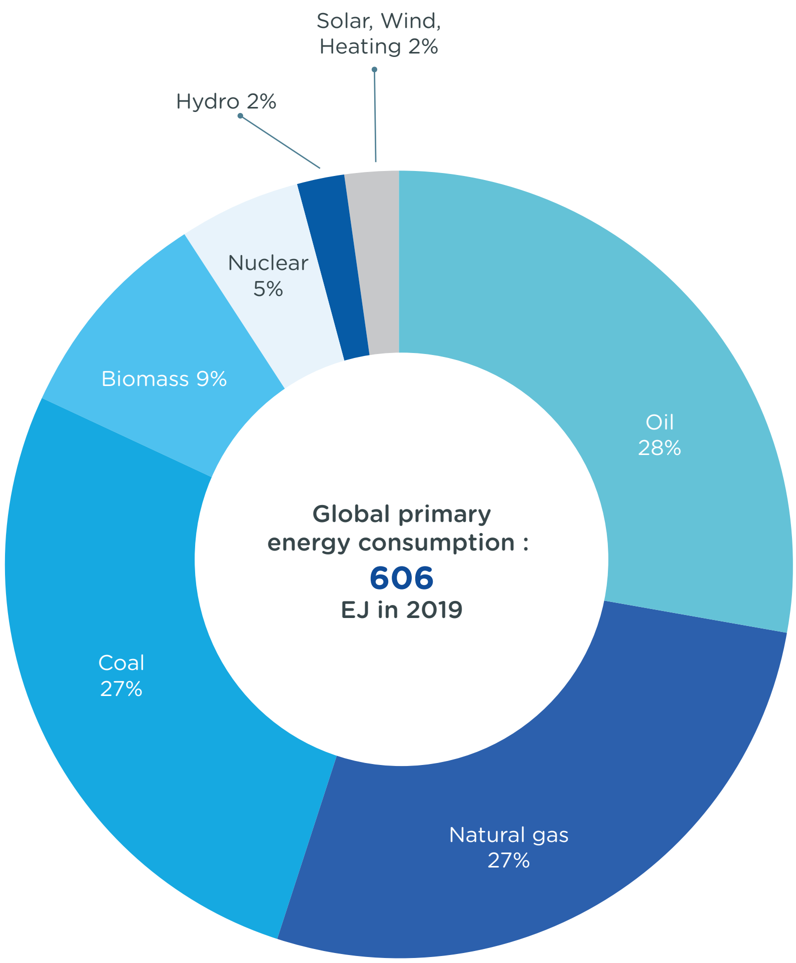


Figure 2.4 : Overall energy consumption by primary energy source (in percent and EJ)
Source : IEA Key World Energy Statistics 2021

[76]See chapter 4 for an explanation of the methods of energy conversion
[77]Source : IEA (International Energy Agency) (2021) Key World energy statistics 2021. https://www.iea.org/reports/key-world-energy-statistics-2021/energy-balances. All rights reserved.

	2000	2010	2019	CAGR 2000 - 2019	CAGR 2010 - 2019
Oil demand (EJ)	131	151	170	+1,4 %	+1,3%
Gas demand (EJ)	47	57	69	+2,0%	+2,2%
Coal demand (EJ)	23	44	39	+2,9%	-1,3%
Total energy demand (EJ)	294	370	419	+1,9%	+1,4%
Electricirty demand (EJ)	46	64	82	+3,1%	+2,8%
GDP US$ billion	48 313	64 894	84 165	+3,0%	+2,9%
Population (billion)	6,1	6,9	7,7	+1,2%	+1,2%

Figure 2.5 : Key figures concerning the final energy consumption in the world
Source : IEA World Energy Balances 2021

ELECTRICITY CONSUMPTION, A VECTOR FOR DECARBONIZATION OF THE ECONOMY, IS GROWING FASTER THAN PRIMARY ENERGY CONSUMPTION

Electricity consumption is rising rapidly

Electricity consumption continues to grow worldwide and reached 22,848 TWh in 2019, whereas it was only 9,702 TWh in 1990. This demand has more than doubled in less than 30 years with near-linear growth. Since 2000, the average annual growth rate of electricity consumption has far exceeded that of primary energy at 3.1% per year compared to 1.9% per year.

When we look at energy consumption in terms of primary and final energy, there is an evident continuous increase in the share of electricity. In 2019, 20% of final energy consumption in the world was electricity, while it represented only 10% in 1973.

This increase in electricity consumption in the world is mainly due to:

- The growing world population, which mechanically increases the demand for energy. According to the UN, the world population could reach 9.7 billion people in 2050 and 11 billion in 2100.[80] Global population was at 7.8 billion people in 2020, compared to 6.1 billion in 2000.
- The increase in electrification. About one billion people still have no access to electricity today,[81] but the trend toward electrification is continuing in developing countries.
- The increase in the share of tertiary sector activities, especially in developed countries. In France, for example, it has increased from 42% in 1962 to 75.9% in 2017[82].
- The increase in the consumption of electric central-heating and air conditioning by individuals.
- The increase in the number of electrified processes in industry. And the development of IT and telecommunications.

ever for policies to reduce emissions and achieve carbon neutrality in

[78]Source : IEA (International Energy Agency) (2020) World Energy Outlook 2020, https://www.iea.org/reports/world-energy-outlook-2020 All rights reserved.
[79]Compound annual growth rate
[80]https://www.un.org/fr/sections/issues-depth/population/index.html#:~:text=Selon%20les%20projections%2C%20la%20population,individus%20vers%20l'an%202100.
[81]https://ourworldindata.org/energy-access
[82]https://www.vie-publique.fr/fiches/269995-les-grands-secteurs-de-production-primaire-secondaire-et-tertiaire

countries committed to the energy transition, which of course assumes that this electricity production is itself decarbonized.

As analyzed below, the substitution of decarbonized electricity for fossil fuels will make it possible to limit GHG emissions, particularly in the transport and industry sectors.

Electricity is used in all consumption sectors, particularly in industry (42%) and residential (27%) areas.

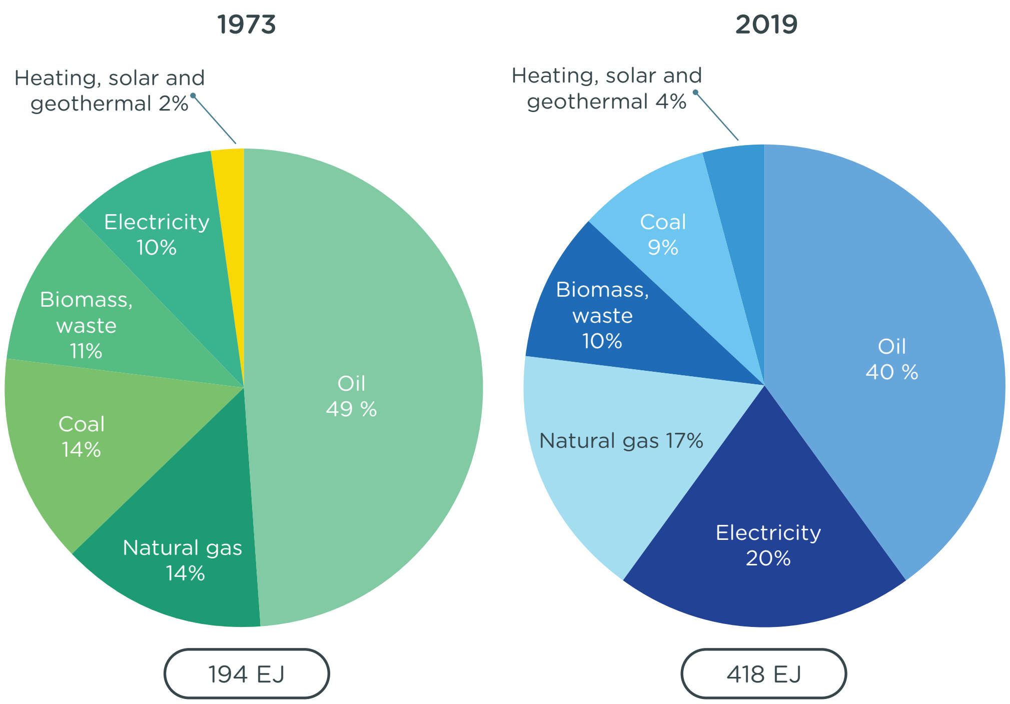


Figure 2.6 : Evolution of the world final energy consumption by source in percentage
Source : IEA Key World Energy Statistics 2021

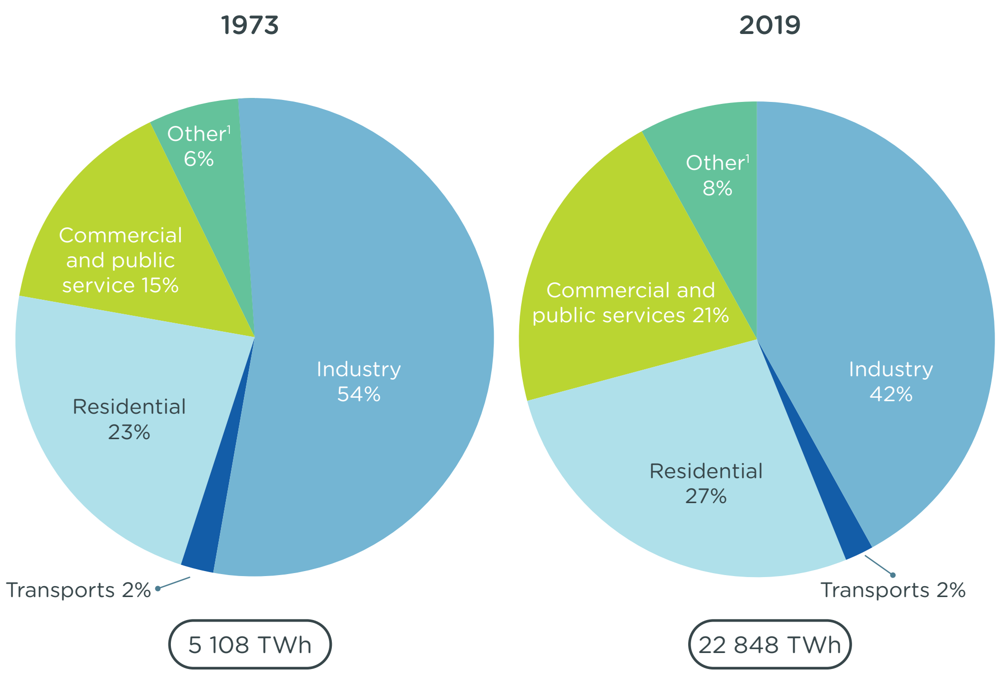


Figure 2.7 : Distribution of final electricity consumption in the world in TWh and percentage
Source : IEA Key World Energy Statistics 2021
Note: Other: self-consumption of power plants, hydrocarbon extraction

Decarbonization of electricity production

As noted above, for the substitution of electricity for fossil fuels to result in lower GHG emissions, the sources of electricity production themselves must emit less GHGs. This is a major challenge of the energy transition.

Figure 2.8 shows the evolution of these sources over time, with a strong increase in solar and wind power in particular. With energy transition policies and public incentives for investment in renewable energies, their share in the global electricity mix should continue to grow. In 2018, the share of renewable energies (hydro, wind, solar, biomass) in the world's electricity production amounted to 27% (see Figure 1.7 - World electricity production by source (1990 - 2019).

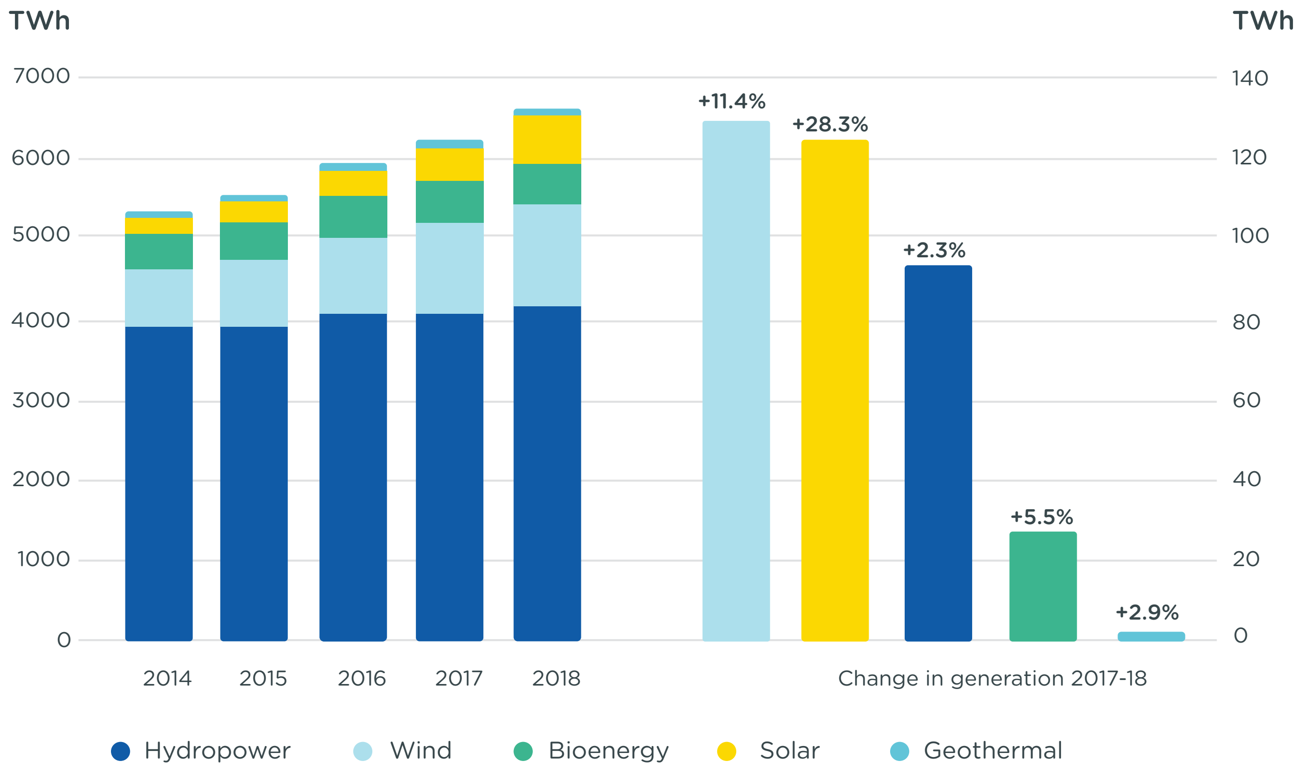


Figure 2.8 : : Growth in renewable electricity generation worldwide between 2014 and 2018
Source : IRENA, July 2020

ENERGY CONSUMPTION BY SECTOR

At the beginning of this chapter, we described the most appropriate energy sources for each use. By using the same segmentation of sectors, we can analyze their share of global energy consumption, the evolution of their consumption and the energy sources used.

Electricity should increasingly be produced from decarbonized and domestic primary energy sources. When this is the case, as illustrated above, the increase in its use will not only decarbonize the economy but also increase energy independence.

The most energy-intensive sectors in 2018 were: transport (32%), industry (31.5%) and residential (23.2%%).[83]

Figures 2.9 and 2.10 show, by sector, the growth in energy demand and the distribution of energy sources:

- Growth in demand in the transport sector is strongest, with almost all (92%) of the final energy consumed coming from oil. The growing share of electric vehicles (if powered by decarbonized electricity) will reduce GHG emissions from this sector.[84] Electric vehicles, which represented 7 million vehicles in 2019, have experienced a very strong growth in sales in 2020,[85] reaching 11 million units[86]. They now represent 0.9% of the global vehicle inventory. The number of electrified light vehicles should reach 350 million in 2030 and nearly 2 billion in 2050 in the "Net Zero by 2050" or NZE scenario of the IEA.[87]
- In the residential sector, electricity represents 37% of final energy consumption and gas 38%. The challenge here is mainly to reduce consumption in new buildings through innovation in construction, standards and regulations and by the renovation of existing buildings. Technological progress (such as LED bulbs[88] for lighting or heat pumps for heating) is decreasing energy consumption.
- The IT and telecommunication sector, which, thanks to connected objects in particular, can better control energy consumption, is experiencing a consumption increase with the growing use of digital technology. According to some projections[89] it could reach between 10 and 20% of global energy consumption by 2030. Operators in this sector, and in particular those of data centers housing data servers, have begun to implement policies aimed at limiting this consumption growth.

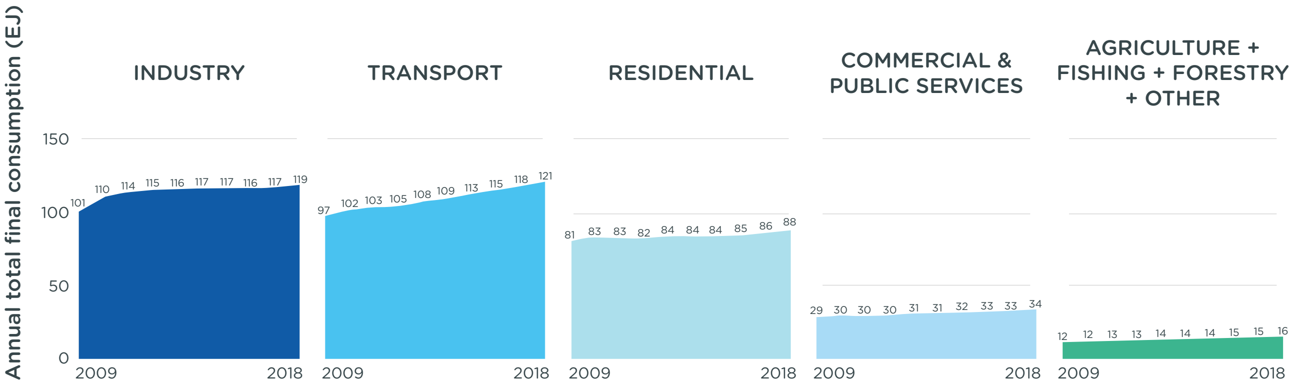


Figure 2.9 : Evolution of final energy consumption by sector (2009 - 2018) in EJ
Source : IEA (International Energy Agency) (2020) World Energy Outlook 2020, https://www.iea.org/reports/world-energy-outlook-2020 All rights reserved.

[83] IEA (2020)
[84] See chapter 3
[85] Source : IEA (International Energy Agency) (2020) Global EV Outlook 2021. All rights reserved. https://www.iea.org/reports/global-ev-outlook-2021
[86] Source : IEA (International Energy Agency) (2020) Global EV Outlook 2021. All rights reserved. https://www.iea.org/reports/global-ev-outlook-2021
[87] Source: IEA (International Energy Agency) (2020) Net Zero by 2050 - A roadmap for the global Energy Sector, May 2021. All rights reserved. https://www.iea.org/reports/net-zero-by-2050
[88] A LED bulb consumes 10 times less electricity than an incandescent bulb, and 6 to 8 times less than a halogen bulb. https://www.quechoisir.org/guide-d-achat-ampoules-basse-consommation-led-n11547/#:~:text=Une%20ampoule%20%C3%A0%20LED%20consomme,fois%20moins%20qu'une%20halog%C3%A8ne.
[89] https://www.enerdata.net/publications/executive-briefing/between-10-and-20-electricity-consumption-ict-sector-2030.html

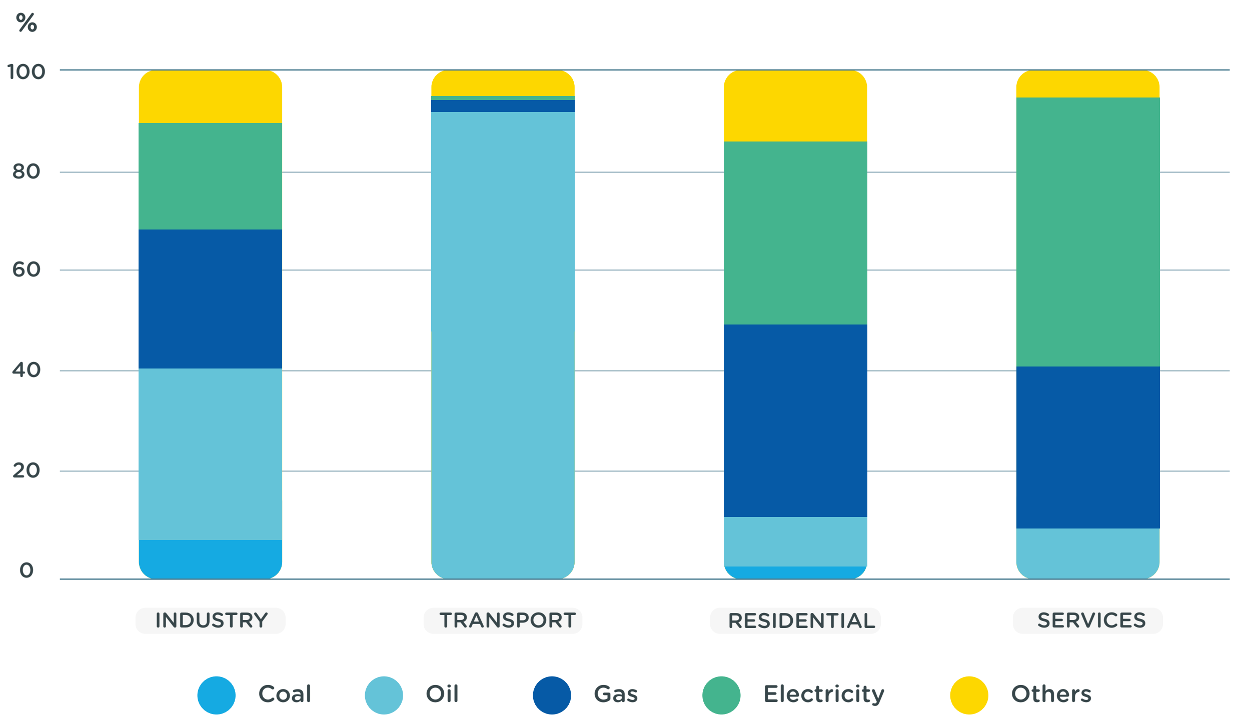


Figure 2.10 : Final energy consumption by sector and source in 2018 in OECD countries (in percent)
Source : IEA (International Energy Agency) (2020) Key World energy statistics 2020. https://www.iea.org/reports/key-world-energy-statistics-2020. All rights reserved.

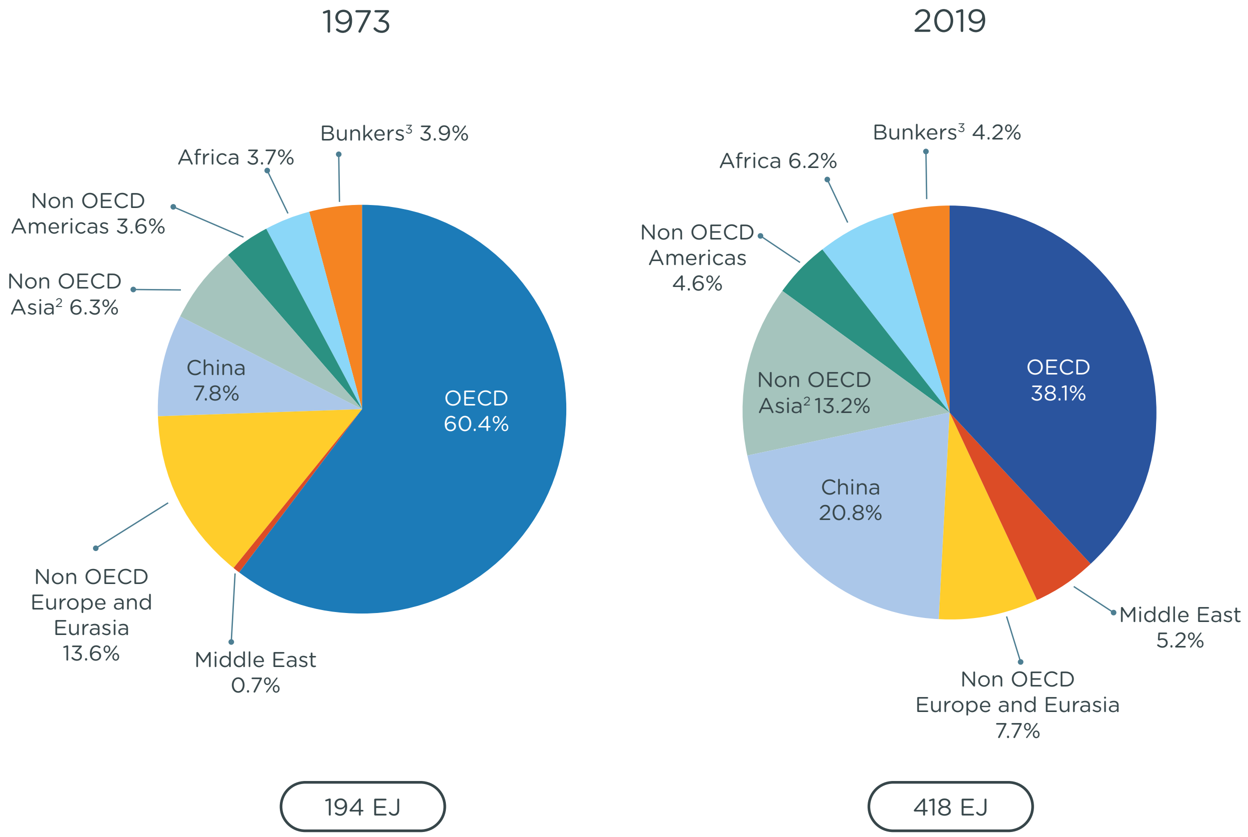


Figure 2.11 : Evolution of energy consumption by geographical area (1973 - 2018) in percentage and Mtoe
Source : IEA (International Energy Agency) – Key World Energy Statistics 2021. All rights reserved.
https://www.iea.org/fuels-and-technologies/electricity

THE EVOLUTION OF ENERGY CONSUMPTION, A CONTRAST BETWEEN DEVELOPING AND DEVELOPED COUNTRIES

While global energy consumption continues to grow, it is changing in different ways in different regions. In fact, there are different dynamics between developed and developing countries: the latter have an increasing consumption while that of developed countries is tending to stagnate, in particular because of energy efficiency efforts. This is illustrated by Figure 2.11: while OECD[90] countries accounted for 60% of world consumption in 1973, they account for only 38% in 2018.

Among non-OECD countries, China's share of global consumption has risen from 7.8% in 1973 to 21% in 2019, while the total volume of energy consumed has more than doubled, from 194 EJ to 418 EJ. At the same time, the share of Africa and non-OECD Asian countries (excluding China) doubled, from 3.7% to 6.2% and 6.3% to 13.2% respectively.

In 2019, while energy consumption increased by 3.1% in China, it decreased by 1.7% in Europe and by 1% in the United States.

Limiting the amount of energy consumed in the world would represent a first step towards meeting the climate challenge and limiting GHG emissions. Given the growth in the world's population and the link between living standards and energy consumption, energy efficiency is an essential lever for the energy transition.[91]

[90] https://www.oecd.org/fr/apropos/membres-et-partenaires
[91] For example, in 2008 the European Union adopted the Energy-Climate package which aimed to increase energy efficiency by 20% by 2020. This objective has been achieved. In the same way, energy intensity has decreased by 2.5% in OECD countries in 2019.

CDP PER CAPITA VS. ENERGY USE, 2015

Annual energy use per capita, measured in kilowatt-hours per person vs. gross domestic product (GDP) per capita, measured as 2011 international - $.

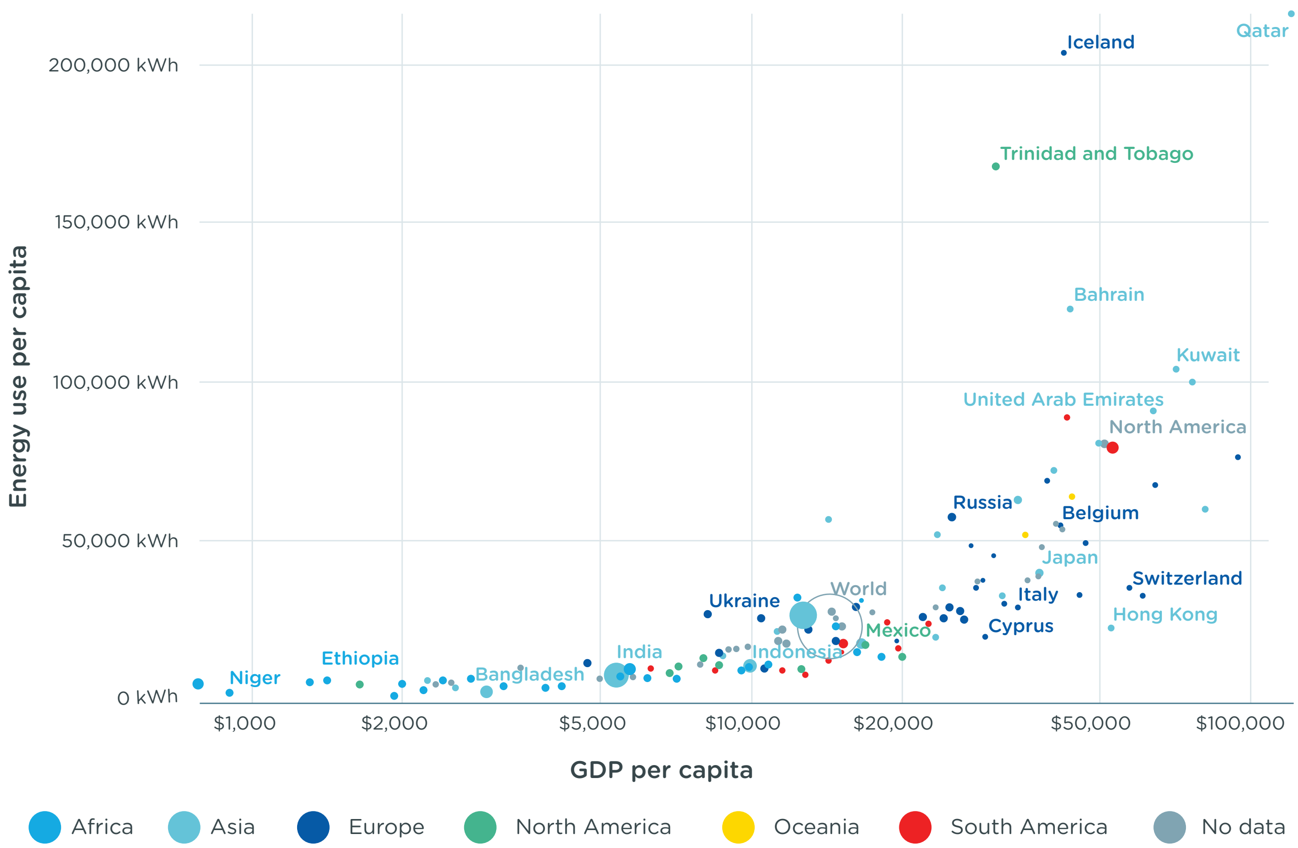


Figure 2.12 : Correlation between standard of living and energy consumption (GDP / energy used in kWh per capita) in 2015
Source : IEA (International Energy Agency) via The World Bank. All right reserved.
https://ourworldindata.org/grapher/energy-use-per-capita-vs-gdp-per-capita

Energy consumption is linked to standards of living

Figure 2.12 illustrates the correlation between GDP[92] per capita (which is a good indicator of living standards) and energy consumption in 2015

Energy consumption is increasing in developing countries

In developing countries, energy consumption has increased drastically over the last 50 years, with exponential acceleration in the early 2000s. This upsurge is mainly driven by the economic development of the giants: China and India. It is also evident that between 2017 and 2018, China was the leader, accounting for more than 75% of the increase in global energy consumption, with followed by India and Indonesia.[93]

The increase in the standard of living of the populations of these countries, induced by economic development, has caused their energy consumption to bound forwards.

Meeting this growing demand for energy will be an answer to the many challenges that developing countries must face:

- Improving the quality of daily life, by automating certain mechanical or manual tasks,
- Contributing to the health of people,
- Improving education through better equipped classrooms during the day and with lighting in the evening.

[92]GDP: Gross Domestic Product
[93]Source : IEA (International Energy Agency) – World Energy Balance 2020. All rights reserved. https://www.iea.org/fuels-and-technologies/electricity

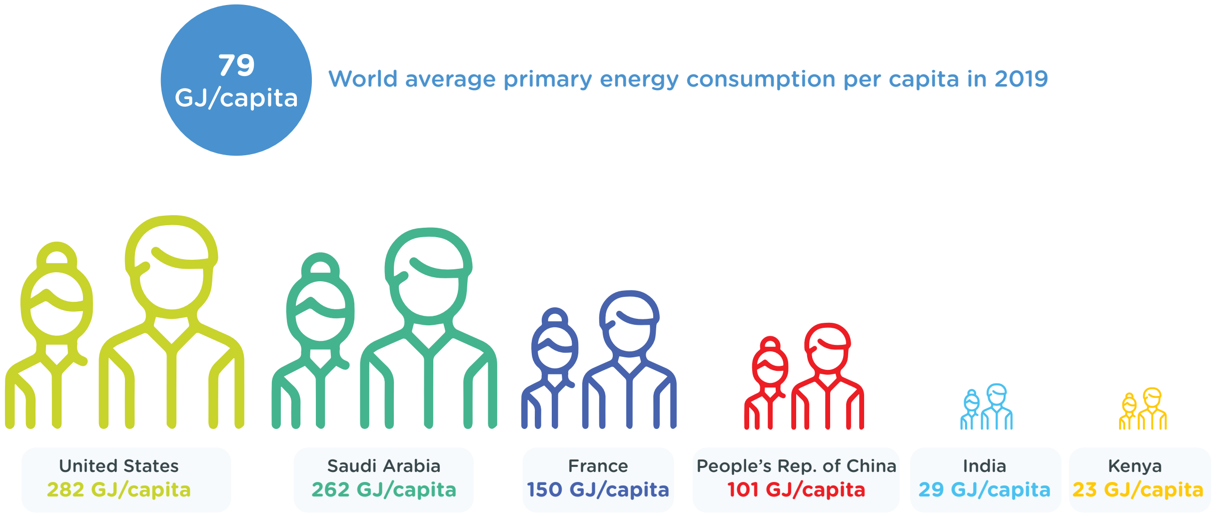


Figure 2.13 : Examples of average energy consumption per capita in developed and developing countries
Source : IEA (International Energy Agency) (2021) Key World Energy Statistics 2021, https://iea.blob.core.windows.net/assets/52f66a88-0b63-4ad2-94a5-29d36e864b82/KeyWorldEnergyStatistics2021.pdf All rights reserved.

- Developing the local economy by allowing people to work in sectors locally other than agriculture, hereby curbing the ongoing exodus to cities in search of work.

Inhabitants of developing countries tend to adopt a very energy-consuming way of life, in the same way as the developed countries did before reaching their current level of comfort.

In the context of the energy transition, the continued development of the least developed countries will require strong technological and financial support from developed countries to make the transition to a low-carbon economy and energy system, and in less than it took for the current advanced economies.

This includes notably:

- Encouraging decentralized and decarbonized energy production models to overcome the lack of electrification, especially in Africa
- Increasing electrification and developing connections between national electricity grids to ensure a secure electricity supply
- Developing final energy consumption models centered around electricity, itself produced from decarbonized energies
- Transferring technologies from industrialized countries to improve energy efficiency, etc.

Article 6 of the Paris Agreement is also particularly important because it encourages voluntary international cooperation as a way facilitating the larger ambitions.

Energy consumption is stagnating or falling in developed countries

In these countries, the situation is different. The public policies implemented over the past decades to control energy consumption have actually borne fruit.

In 2019, primary energy consumption in the United States decreased by 0.8% compared to 2018. Things were similar in France, where primary energy consumption decreased the same year by 1.4%.[94]

Another illustration of this downward trend comes from oil, whose consumption rose from 1,924 to 2,397 million tonnes between 2010 and 2019 for non-OECD countries, demand decreased from 2,140 to 2,077 million tonnes.

In developed countries, many mechanisms have been put in place to improve energy efficiency. For instance:

- Legislation at the European level, for example with the "Energy and Climate" directive and in many European countries with energy transition laws
- Regulations that impose construction standards for new buildings (low energy consumption or positive energy buildings
- The regulation on manufacturing that imposes the reduction of consumption of ICE units by limiting the CO_2 emissions of vehicles sold,
- Traffic restrictions in certain cities for the most energy-consuming and highest emitting vehicles,
- Financial or fiscal incentives, e.g.: for the energy renovation of buildings,
- Energy-saving certificates which, in France for example, require energy sellers to take measures that enable their customers save energy.

There is also a change in consumer attitudes with the development of:

- Self-consumption, which consists in users producing part of their electricity themselves (mainly thanks to solar energy).
- Micro-grids which confirm the determination of a district's inhabitants, for example, to better control their electricity consumption and to exchange it between one another.
- Smart cities that are also less energy-consuming etc.

[94]Source : IEA (International Energy Agency) – World Energy Balance 2020. All rights reserved. https://www.iea.org/fuels-and-technologies/electricity

This type of legislative or regulatory framework and these changes in behavior are essential elements in promoting the transition to a carbon-neutral world (see Chapter 5).

As indicated in this chapter, population growth and development generate a growing demand for energy, particularly in developing countries. Within this higher energy demand, electricity demand is expected to grow faster than other energies and its share in final energy consumption is also liable to increase, since it is a key element of the "low-carbon" policies.

3

Climate change

3.1 Introduction

The world's climate has varied greatly over the past several million years, with periods of glaciation and interglacial warming.[95] These phenomena have not yet been fully explained or understood. The changes took place over very long periods, allowing animal and plant species time to gradually adapt to them.

These climate changes were the origin of human migrations. For instance, the Greek philosopher Theophrastus, in his work "Of the Winds", already wrote that on the Cretan mountains, one could see ruins of ancient cities that had long been abandoned for reasons of changing climate.

[95] IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Climate variations began to be studied scientifically in the 18th century, particularly with the advancements made in paleontology, but it was only after the Interwar Period that climatology became recognized as a real science.

Climate change as we commonly refer to it, is one of the major challenges of the 21st century. The term is derived from the lasting changes in the climate caused by anthropogenic activities (related to humans). These climate changes are occurring at much faster pace than ever before.

The IPCC (Intergovernmental Panel on Climate Change)[96] was formed in 1988 to synthesize the work published each year by thousands of researchers who analyze climate trends and forecasts on a global scale. Its mission is also to provide decision-makers with this knowledge and to alert them of key elements which may be pertinent in their policy development.

In GT1 of the sixth evaluation report published on 9 August 2021[97], the IPCCstated that there is no further doubt concerning the fact that the warming of the atmosphere, ocean and emerged land is due to human activity. It also reports that there has been an unprecedented number of changes recorded since thousands, or even hundreds of thousands, of years, and that some phenomena already underway, for instance the constant rising of the sea level, will be irreversible for the next hundred to thousand years. The IPCC warns that if anthropogenic emissions are not slowed down, there will be further warming of our planet beyond the threshold of 1.5°C which may be breached in the next 20 years, causing lasting changes to the climate system and to biodiversity. This climate change will increase the likelihood of severe, widespread and irreversible consequences for people and ecosystems, with varying degrees of intensity regionally, but with increased with continued warming globally.

[96]The IPCC was created in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP).
[97]https://www.ipcc.ch/site/assets/uploads/2021/08/IPCC_WGI-AR6-Press-Release_fr.pdf

3.2 The greenhouse effect

The greenhouse effect[98] is a natural phenomenon. Because of it, the Earth's surface enjoys an average temperature of about 15°C (compared to -18°C without the greenhouse effect).

A manmade greenhouse is a closed glass structure that allows the sun's rays to pass through the panes to warm its inside while preventing most of the heat within from escaping.

[98] https://www.ademe.fr/sites/default/files/assets/documents/guide-pratique-changement-climatique.pdf

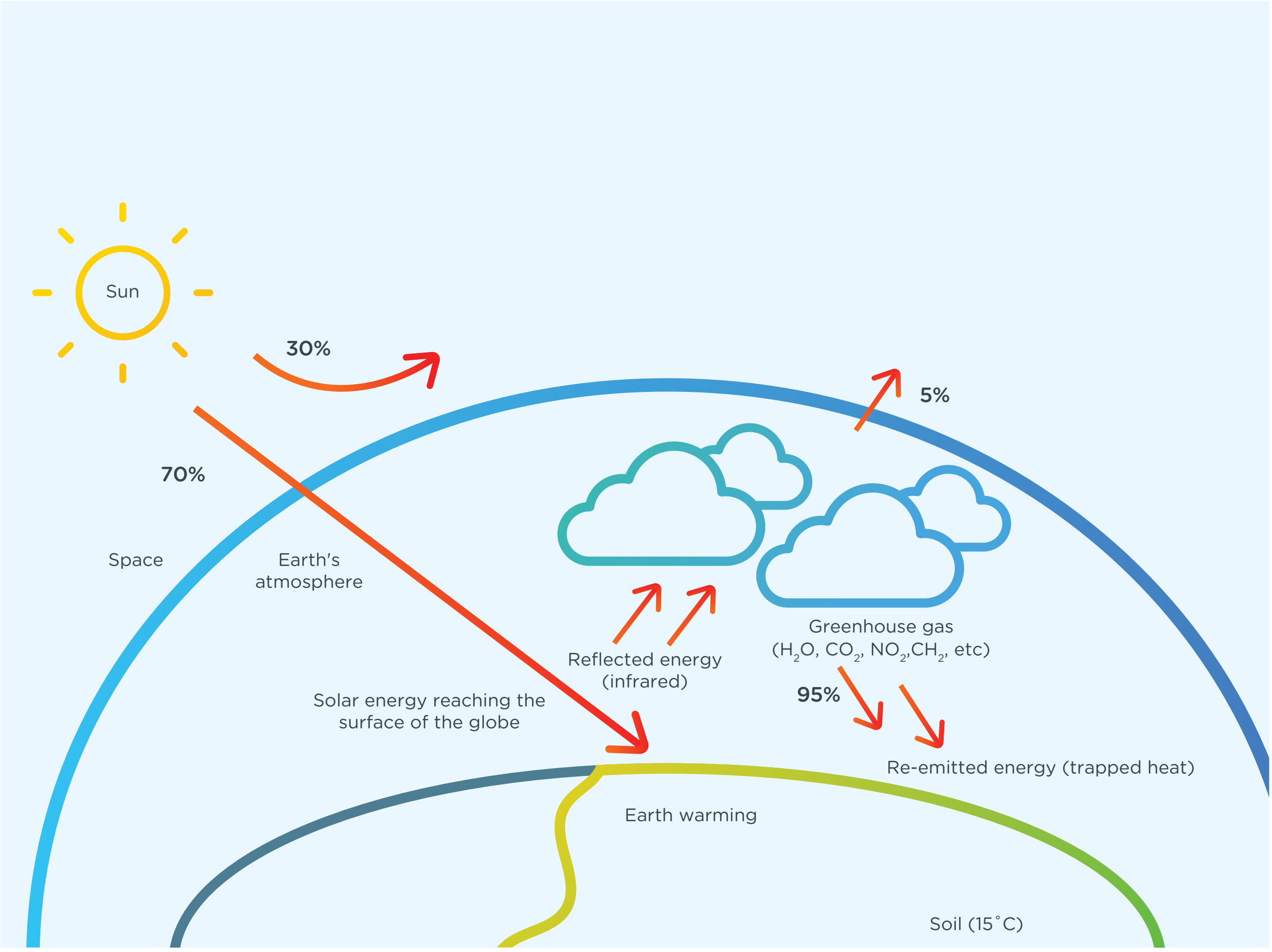


Figure 3.1: The greenhouse effect
Source : US Energy Information Administration

When the sun's rays enter a greenhouse, the interior heats up and emits infrared radiation.[99] But these infrared rays are blocked by the glass, which is opaque to infrared radiation, heating the interior even more. This is what is called a greenhouse effect.

In this analogy, the earth's atmosphere is equivalent to the glass surface of the greenhouse. More precisely, it is the GHGs in the atmosphere that play this role: they allow the sun's rays to pass through to the Earth's surface, but prevent the infrared radiation emitted by the ground from re-entering space. In this way, they trap solar energy near the ground, thereby increasing the global temperature.

[99]https://www.futura-sciences.com/sciences/definitions/physique-infrarouge-1011/

3.3 Greenhouse gases (GHGs)

Greenhouse gases (GHGs) occupy less than 0.1% of the atmospheric volume. Water vapor, which fluctuates between 0.4 and 4%, is the main greenhouse gas.[100] It absorbs the thermal energy in the air very efficiently but does not accumulate in the atmosphere like other GHGs. Its life span is very short because it precipitates quickly in the form of water or snow.

[100] Key figures on climate – Edition 2021 – I4CE

The "anthropogenic" greenhouse effect is due to the increase in the concentration of GHGs in the atmosphere due to emissions generated by human activitiess[101]:

- Carbon dioxide (CO_2) of human origin, produced for the most part by the combustion of fossil fuels (coal, oil, gas), but also by certain industrial processes such as the manufacturing of cement or steel.
- Methane of human origin (CH_4, also called natural gas) produced by the combustion of organic matter such as wood, the breeding of ruminant animals, the cultivation of rice, the fermentation of household waste, and by the extraction of oil, gas and coal. It is also worth noting that climate change could cause the disintegration of methane hydrates (trapped in solid form as ice) by warming the ocean bed and releasing their methane into the atmosphere. Significant quantities of methane could also be released from soils, which until now have been permanently frozen, by the melting of permafrost.[102]
- Halocarbons[103] from refrigerant gases (air conditioning, cold chains), propellants in aerosol cans, and in certain industrial processes (computer components, telephones, plastic foam).
- Nitrous oxide (N_2O) which comes from the use of fertilizers and certain chemical processes.
- Tropospheric ozone (O_3)[104] is a secondary pollutant, i.e. it comes from the formation of pollutants generated by human activities, such as automobiles.
- Fluorinated gases (CFC, HCFC, PFC, HFC, SF6, NF3). SF6 is for example used as an insulating gas in electrical transformer substations.[105]

[101]https://archive.ipcc.ch/publications_and_data/ar4/wg1/en/faq-1-3.html
[102]https://jancovici.com/changement-climatique/risques/faut-il-redouter-les-hydrates-de-methane/
[103]This is a vast family of gases obtained by replacing, in a hydrocarbon molecule (propane, butane, or octane, found in gasoline, are hydrocarbons), hydrogen by a halogen gas (fluorine, chlorine ...).
[104]The troposphere is the lowest layer of the atmosphere, closest to the ground
[105]This use is now prohibited.

These GHGs have different lifespans in the atmosphere, and varying warming abilities on the atmosphere compared to CO_2, as explained below.

GHGS LIFE SPAN IN THE ATMOSPHERE: CO_2 EQUIVALENT

The "CO_2 equivalent" (CO_2eq) is a unit created by the IPCC to compare the impacts of these different GHGs on global warming and to be able to add up their emissions.

In concrete terms, the CO_2 equivalent consists of assigning a "Global Warming Potential" (GWP) to a GHG for a given period in relation to the CO_2 that serves as a standard (and whose GWP is therefore set at 1). It measures the estimated greenhouse effect of a GHG.

One of the complexities of this equivalent comes from the fact that different GHGs have different lifespans in the atmosphere. Their GWP must therefore always be assessed in relation to a given time scale: a tonne of methane has a GWP of 34 on a 100-year scale but 86 on a 20-year scale, given its shorter lifespans in the atmosphere compared to CO_2. When the time scale considered is not specified in the emissions assessments, it is set "by default" at 100 years.

<table>
<tr><th></th><th>20 years</th><th>100 years</th><th>Origin of anthropogenic emissions</th></tr>
<tr><td>CO_2 (CARBON DIOXIDE)</td><td>1</td><td>1</td><td>Fossil fuel combustion, industrial processes and deforestation</td></tr>
<tr><td>CH_4 (METHANE)</td><td>86</td><td>34</td><td>Landfill, agriculture, livestock and industrial processes</td></tr>
<tr><td>N_2O (NITROUS OXIDE)</td><td>268</td><td>298</td><td>Agriculture, industrial processes, use of fertilizers</td></tr>
<tr><td>CF_4 (CARBON TETRAFLUORIDE)</td><td>4950</td><td>7350</td><td rowspan="2">Sprays, refrigeration, industrial processes</td></tr>
<tr><td>HFC-134a</td><td>3790</td><td>1550</td></tr>
</table>

Figure 3.2: Global warming potential (CO_2eq) for 20 and 100 year periods
Source : Source : IPCC, 2013 : Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.[107]

[106]Indice introduced in the "IPCC First Assessment Report.
[107]https://archive.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter08_FINAL.pdf

THE CONCENTRATION OF CARBON IN THE ATMOSPHERE

Since pre-industrial times, the concentration of CO_2 in the atmosphere has increased significantly due to emissions from human activities.

The concentration of atmospheric CO_2 has increased from about 277 parts per million (ppm) in the pre-industrial era to 410 ppm in 2019. More than half of this increase in emissions has occurred in the last 40 years.[108]

According to the IPCC[109] it is very likely that the 1.2° - 1.9°C range will be reached in every one of the different scenarios analysed over the 2020-2040 period, that is, an average threshold of 1.5°C to 1.6°C will be reached or passed in the next 20 years. The challenge is to subsequently limit warming at 1.5° between now and 2100 (and the impacts will already be considerable) and avoid scenarios where temperatures could rise to 2.7°, 3.6° or even 4.4°. In a study updated in 2018, the IPCC assessed the impact of a trajectory limiting global warming to 1.5°C at the end of the 21th century, which would require a reduction of about 45% in emissions by 2030 and would bring the concentration to 430 ppm by 2100.

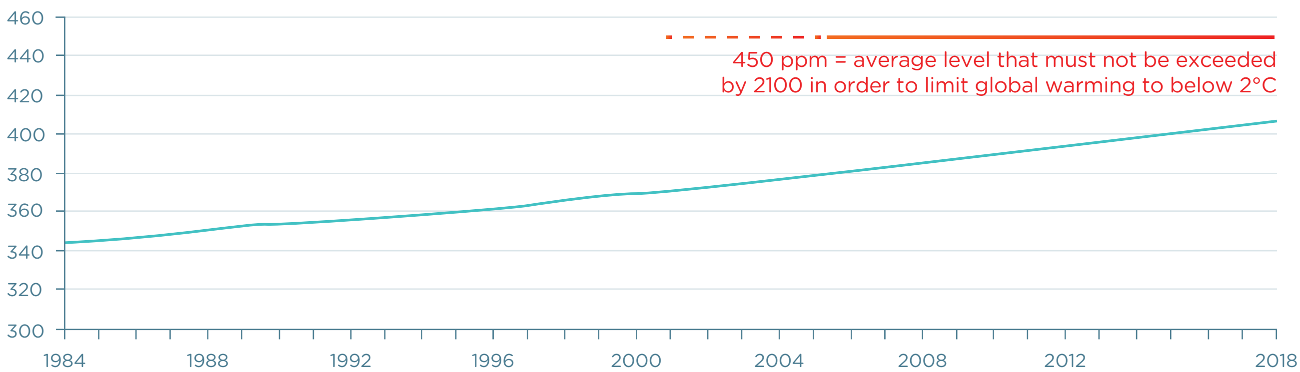


Figure 3.3: Atmospheric CO_2 concentration (in parts per million ppm)
Source : French Data lab based on the World Data Centre for Greenhouse Gases (WDCGG), part of the World Meteorological Organization (2018)

[108]Source: NOAA-ESRL; Scripps Institution of Oceanography; Friedlingstein et al 2020; Global Carbon Budget 2020
[109]https://www.ipcc.ch/site/assets/uploads/2018/02/AR5_SYR_FINAL_SPM_fr.pdf
[110]https://www.ipcc.ch/site/assets/uploads/sites/2/2019/09/IPCC-Special-Report-1.5-SPM_fr.pdf

3.4 Carbon sinks

Carbon sinks (natural or artificial) store carbon dioxide from the carbon cycle and the atmosphere. Carbon sinks influence the world's climate by helping to reduce the amount of atmospheric CO_2.

Over the last ten years, of the 40 Gt of CO_2 released on average per year by human activities, the atmosphere has absorbed 19 Gt, terrestrial sinks (biosphere and soils) 12 Gt, and the oceans 9 Gt. The atmosphere is the carbon sink most strongly activated by anthropogenic activities: it has absorbed nearly 50% of all carbon emitted over the last 50 years.[111]

[111]https://www.globalcarbonproject.org/carbonbudget/20/presentation.htm

NATURAL CARBON SINKS

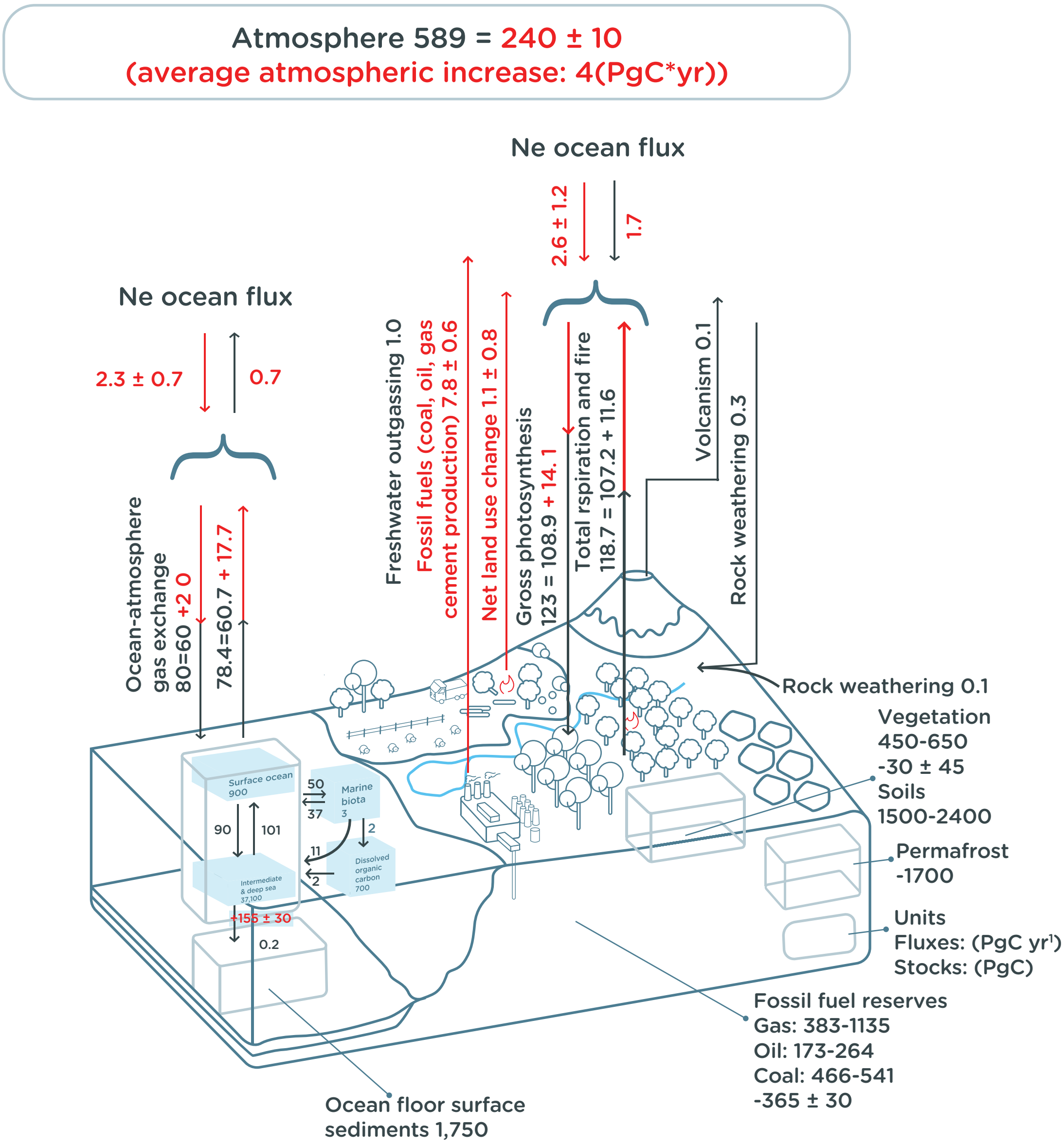
These consist mainly of vegetation and oceans that absorb about half of human CO_2 emissions. They contribute to reducing the presence of GHGs in the atmosphere, thereby limiting the climate warming of the planet.

Forests and Vegetation

Terrestrial plants (forests, dead wood, soils, lawns, peat bogs...) that absorb carbon dioxide through photosynthesis[112] have a net capture balance of about 120 billion tonnes of CO_2.[113] Peatlands - wetlands with decomposing plant residues - have a particularly interesting role to play, capturing a quarter of the carbon in the soil while occupying only 3% of the earth's surface.[114]

It is logical that more carbon in the atmosphere means boosted photosynthesis causing plans to grow more. According to a study which appeared in 2017[115], plants have managed to adapt and absorb CO_2 by means of photosynthesis, in proportion to the carbon increases on Earth. However, in the same way as drought and other events, the effects of climate change could have a disturbing effect on interactions between the environment and the plants, changing their absorption capabilities. This makes it essential to take measures to protect natural CO_2 sinks, including forests and other wetlands. Many projects have been developed to preserve or even increase forestation to serve as carbon sinks (as in the REDD+ initiative supported by the Food and Agriculture Organization of the United Nations).

[112]https://www.futura-sciences.com/planete/definitions/botanique-photosynthese-227/
[113]IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Chapter 6
[114]https://theconversation.com/peatlands-keep-a-lot-of-carbon-out-of-earths-atmosphere-but-that-could-end-with-warming-and-development-151364
[115]https://www.novethic.fr/actualite/environnement/climat/isr-rse/les-plantes-absorbent-30-du-co2-mondial-mais-cela-pourrait-ne-plus-durer-147297.html



Note : Numbers represent reservoir mass, also called carbon sinks, in PgC* (1015 gC).

Black arrows and numbers represent exchange flows estimated for the time period prior to industrial era (about 1750), expressed in PgC per year.

Red arrows and numbers indicate annual 'anthropogenic' flows averaged over the 2000–2009 time period

*PgC = Petagrams of Carbon

Figure 3.4: Impact of human activities on the carbon cycle (net balance in GtCO$_2$/year during the 2000's)
Source : IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Chapter 6 [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.[116]

[116]IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Chapter 6. [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

Oceans

Each year, the oceans absorb nearly a quarter of the CO_2 emitted. Today, the increase in CO_2 emissions from human activities is causing two changes in water masses:

- Oceans acidity, up 30% since 1800.
- Climate change causes the surface waters to warm too, reducing the ocean's capacity to absorb CO_2 (CO_2 dissolves more easily in cold water). As a result, more CO_2 is absorbed by the atmosphere, worsening its impact on the climate.

Modeling these natural CO_2 absorption phenomena is very complex, involving many uncertainties. Nevertheless, natural sinks such as forests and oceans only absorb at best about 50% of the CO_2 emitted each year. The stock of CO_2 will therefore continue to increase each year unless purposeful and wide-reaching actions are taken to reduce it. This is where the climate policies come in (see chapter 5).

ARTIFICIAL CARBON SINKS

Artificial carbon sinks are technological processes that prevent the release of CO_2 into the atmosphere in large quantities, known as CO_2 capture, utilization and storage (CCUS)[117]. For example, this could involve capturing carbon in a coal-fired power station (or in a combustion plant or a plant producing hydrogen from fossil gas for example) or directly in the air (via the technology under development "Direct Air Capture"), then conveying it via a pipeline or by maritime transport and storing it underground in a saline cavity or an onshore or offshore oil tank. The reuse of CO_2 in a process that ends in combustion and venting as in the case of synthetic carbon fuels and gases effectively reduces emissions by about 50% according to the IEA. Only the reuse of captured CO_2 that is finally sequestered, makes it possible to avoid or completely eliminate its release into the atmosphere, as in the case CO_2 which which ends up in construction materials for roads or simply wood for buildings.

[117]See chapter 5 on action levers to ensure the energy transition

3.5 Human activity and GHG emissions

GHG emissions reached, according to the calculation methods, between 48.9 and 55.3[118] billion tonnes of CO_2eq in 2018.

[118]UN Environnement – Emissions Gap Reports 2019; data including GHG emissions related to changing land use & World Resources Institute

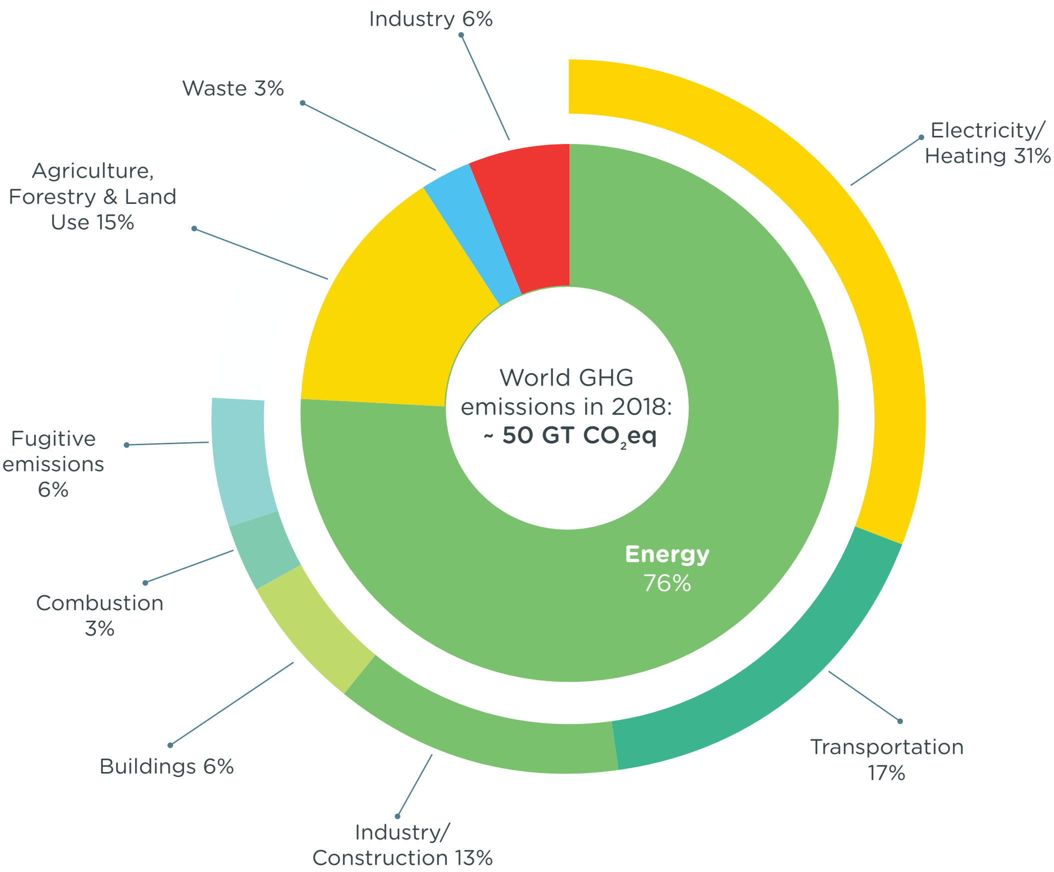


Figure 3.5: Breakdown of GHG emissions by sector in 2018
Source : Climate Watch, World Resource Institute

GHG EMISSIONS BY SECTOR

The main sectors responsible for GHG emissions are energy consumption for industry, transport, buildings, electricity production, heating and air conditioning (67%) and agriculture, particularly due to methane emissions (15%). The remainder is linked to the extraction of hydrocarbons, petrochemicals, and to the production of cement.

GHG EMISSIONS LINKED TO ENERGY

Energy use accounts for 76% of global CO_2eq emissions and electricity for 42% of them[119]. This puts energy at the heart of the challenges of reducing GHG emissions (figure 3.6).

The primary energy sources that emit GHGs (mainly carbon dioxide) are fossil fuels (coal, oil, gas) and biomass (if not replanted).

The electricity sources that emit little or no CO_2eq are nuclear, hydraulic, solar, onshore wind and marine energy. For heat production, they are geothermal sources and the biomass if it is replanted. Note, however, that even if the source of electricity does not produce GHGs, actually building the "production plant" will generate emissions.

Indeed:

- To build a power plant (coal, nuclear, gas, oil, or a dam), construction materials are needed (cement and steel in particular), and their production generates GHG emissions,
- To build a wind turbine or a solar panel, basic materials (aluminum,

[119]https://ourworldindata.org/ghg-emissions-by-sector

glass, etc.) or more complex equipment (semiconductors) are required, and their production emits GHGs.

If we include these "indirect emissions", i.e., those generated during the life cycle, we obtain the total quantity of GHGs emitted and obtain a given quantity of final energy.

The table below shows the total life-cycle emissions of the various electricity sources.

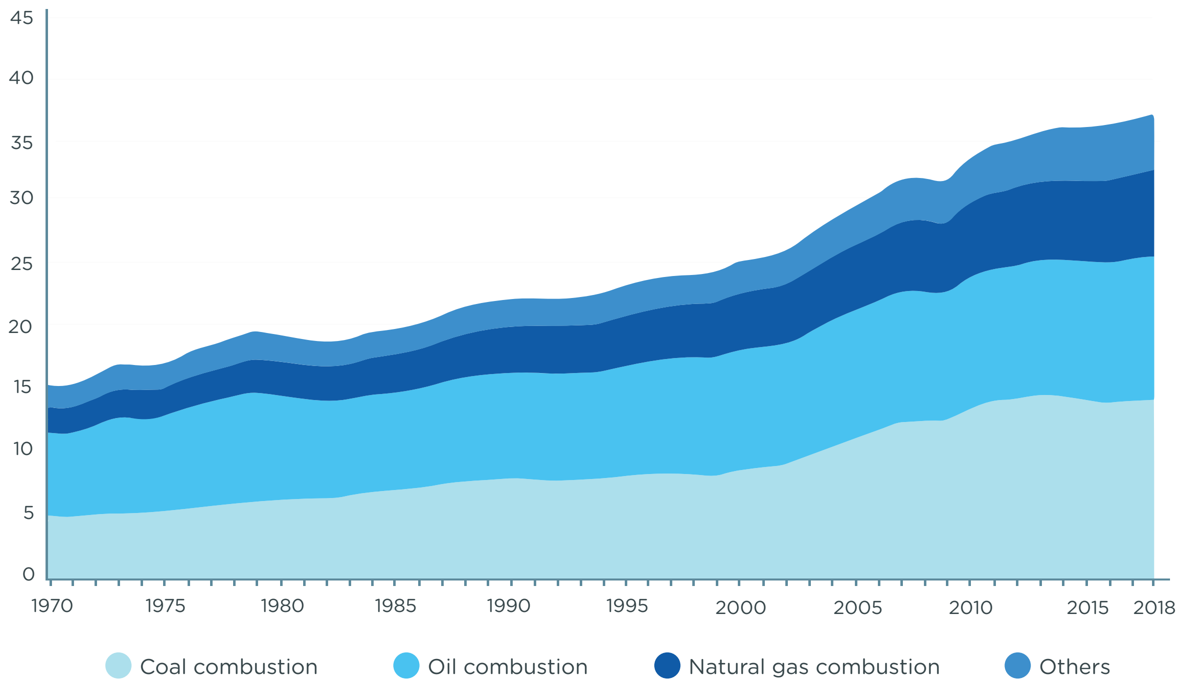


Figure 3.6: CO_2 emissions by fuel in the world (in Gt CO_2)
Source : Ministry of Ecological Transition - Key figures for climate 2021 - France, Europe, and World

ELECTRICITY SOURCE	AVERAGE VALUE**
Coal (pulverized coal-fired boiler)	820
Heavy fuel	778
CCGT	490
Biomass	320
Solar PV	41
Geothermal	38
Hydropower	24
Nuclear	12
Offshore wind	12
Onshore wind	9

*Figure 3.7: CO_2 equivalent emissions of different electricity generation technologies (CO_2e/kWh)**
Source : IPCC 2014[120]

*Notes : *Emissions calculated over the entire life cycle ** Average values are used. Emission levels vary depending on where the equipment is manufactured and the CO_2 emissions from the local electricity used to manufacture it*

[120]Schlömer S., T. Bruckner, L. Fulton, E. Hertwich, A. McKinnon, D. Perczyk, J. Roy, R. Schaeffer, R. Sims, P. Smith, and R. Wiser, 2014: Annex III: Technology-specific cost and performance parameters. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

GHG EMISSIONS BY COUNTRY

The three countries that emit the most CO_2eq are: China, the United States and India

In 2006, China became the biggest CO_2 emitting country ahead of the United States. The main drivers behind China's CO_2 emissions are its growing population, rising average standard of living, the development of its industrial production (for domestic consumption and for export) and the use of fossil fuels for its electricity production. Europe's biggest emitter of GHGs is Germany, due to its dependence on coal for its electricity production, according to reports by the European Environment Agency.

Their GHG emissions, when compared to the numbers of inhabitants, give a different result mirroring the standard of living and lifestyle of the country concerned. In this case, the biggest emitters are the countries of the Middle East and North America. For the same type of climate and an equivalent level of development, it is evident that some countries consume more energy and emit more GHGs than others (North America vs. Europe).

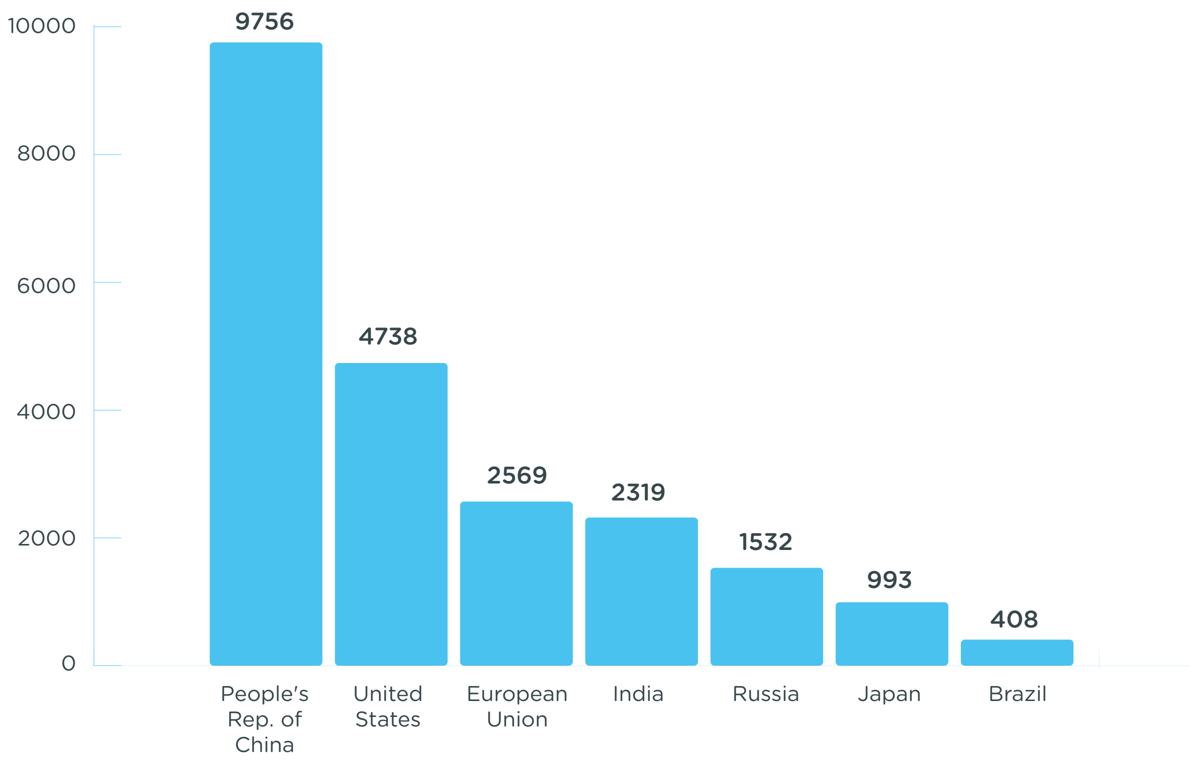


Figure 3.8: Examples of GHG emitting countries in 2019 (in Mt of CO_2)
Source : Source: IEA (International Energy Agency) (2020) World Energy Outlook 2020, https://www.iea.org/reports/world-energy-outlook-2020 All rights reserved.

CO_2 EMISSIONS PER CAPITA WORLDWIDE

CO_2 emissions per capita in selected countries in 2017 (in tons)

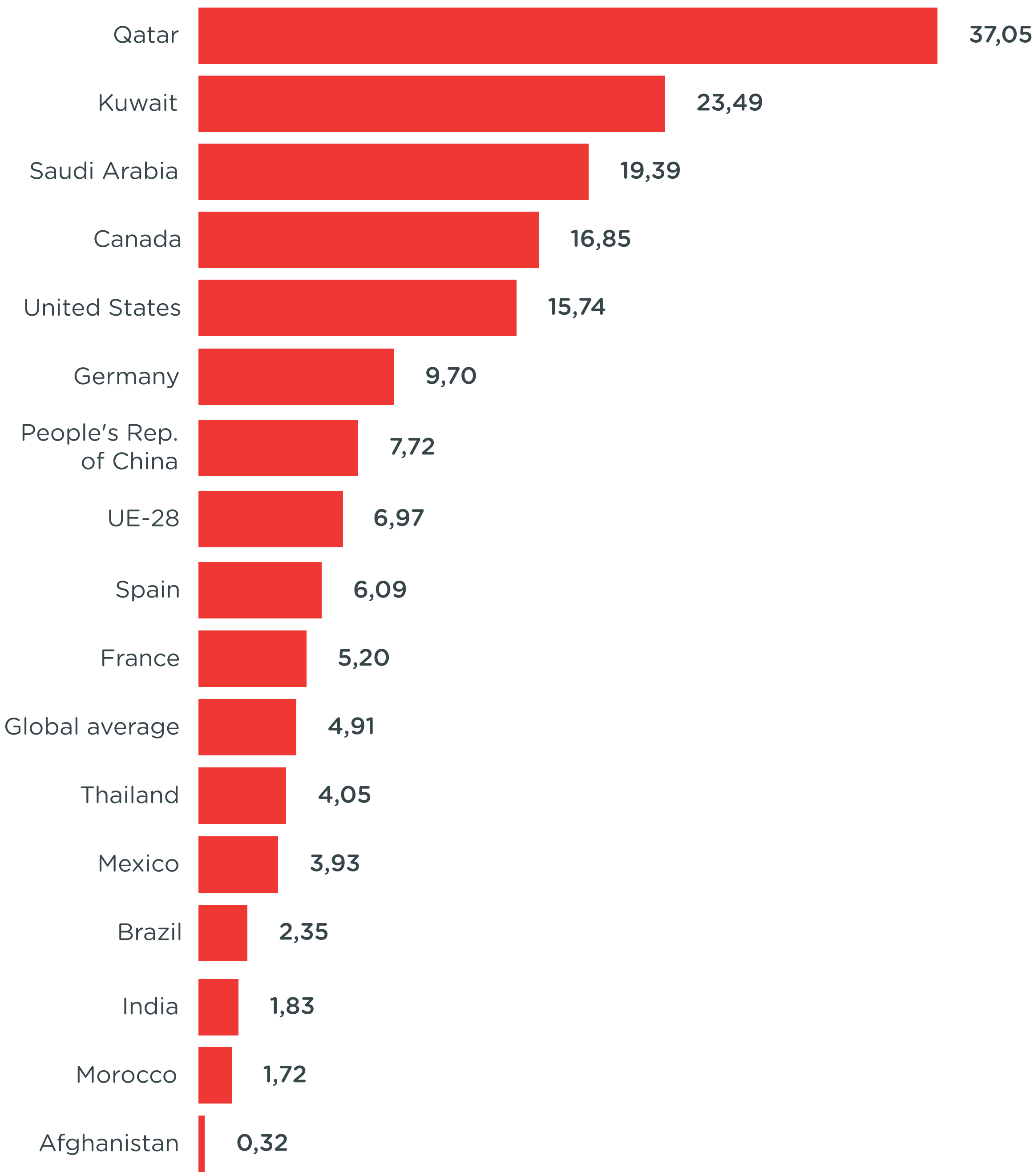


Figure 3.9: CO_2 emissions per capita worldwide (in tons of CO_2, per capita)
Source : European Commission

OUTLOOK FOR GHG EMISSIONS EVOLUTION

In 2018, total global CO_2eq emissions reached 55.3 billion tonnes. In 2020, CO_2 emissions dropped by 6% because of the COVID crisis. This was the biggest drop since World War II according to the International Energy Agency (IEA)[121].

Nevertheless, the situation is contrasted:

- Emissions in China increased by 0.8% during 2020, despite the partial shutdown of its economy in early 2020. In India, emissions have risen again due to the economic recovery and the increased consumption of oil products
- On the other hand, emissions in the United States dropped by 10% due to the decreased consumption of energy products for transport and industry.

The IEA expects emissions to increase in 2021 but notes that, for the first time, signals are stronger in terms of government commitments and "green" stimulus plans, corporate targets, citizen movements, could suggest a reversal of this trend. However, the contents of Working Group 1 of the IPCC's sixth report published in August 2021, which establishes five illustrative scenarios covering the range of possible developments of GHG emissions from human activities, is less optimistic.

The IPCC scenarios are based on different assumptions concerning socio-economic conditions levels of climate change mitigation and air pollution controls. The CO_2 emissions variation (and other GHGs) from 2015 to 2050 in each of the scenarios is represented in figure 3.10.

In all scenarios, total GHG emissions lead to a temperature increase in the middle of the 21st century (compared to the end of the 19th century). At the end of the 21st century, this increase varies between 1°C and 5.7°C depending on the scenario, which leads the IPCC to conclude that a global warming of 1.5°C and 2°C will be exceeded during the 21st century unless strong reductions in GHGs occur in the coming decades.

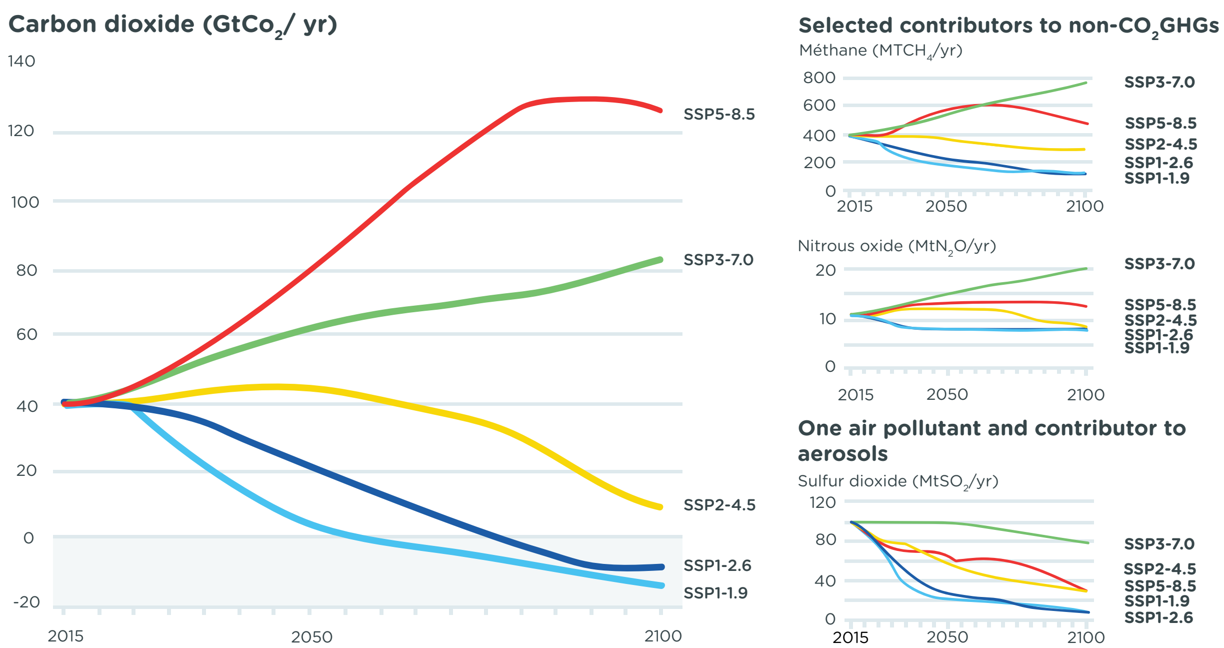


Figure 3.10: Future annual emissions of CO_2 (left) and of a subset of key non-CO_2 drivers (right), across five illustrative scenarios of IPCC

Source : Source : IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press. In Press.

[121] IEA (International Energy Agency) (2020). https://www.iea.org/news/after-steep-drop-in-early-2020-global-carbon-dioxide-emissions-have-rebounded-strongly.

Global warming is a major issue of the 20th century and its link with energy demand is undeniable.

Limiting global warming will require efforts to be made as soon as possible to reduce GHG emissions, but also to capture and sequester them.

By mid-2021, countries representing 70% of CO_2e emissions had or were about to implement laws aiming at carbon neutrality according to the IEA analysis.[122]

[121]IEA (International Energy Agency) (2020) Net Zero by 2050 - A roadmap for the global Energy Sector, May 2021.
https://www.iea.org/reports/net-zero-by-2050

4

Comparison of different energy sources

4.1 Introduction

Comparing energies is not as simple as it might seem.

Most energy reports compare different types of energies by the amount of primary energy needed to produce them. In doing so, other important characteristics of these energies and their various uses are often overlooked.

Primary energies come directly from natural resources: fossil energies or energies linked to the sun - which evaporates water, heats and moves the air, feeds the biosphere or is directly transformed into energy (solar, wind, biomass, hydraulic...). When transformed, primary energies become secondary energies (electricity for example).

In the past, electricity was generated only from fossil fuels. So naturally, to convert a given amount of electricity (secondary energy) into primary energy, reference was made to the amount of fossil energy (primary energy) needed to produce it by burning off this fossil fuel in a power plant. This method continued to be used used during the advent of nuclear electricity in the 1970s, despite the origin of nuclear energy being totally different from that of fossil energies. In a nuclear power plant, the nuclear reaction within the uranium-based fuel is what produces energy in the form of heat. This heat energy will heat water, like the heat energy from gas combustion for example.[123]

[123]This steam is used to turn an alternator which produces electricity.

The hydraulic electricity generation comes from the mechanical energy generated by the waterfall and does not go through the heat energy stage. Converting it into primary energy of fossil type is therefore more difficult to justify. The increase in renewable electricity (solar, wind), has added to the complexity of conversion standards and, depending on the source, the same conversion methods are not always used (see "Going further ")

The fight against climate change requires the use of low GHG-emission energy production technologies to limit GHG concentrations in the atmosphere, a key factor in global warming (see Chapter 3). These low-carbon energy production technologies have very different characteristics from fossil fuel based solutions and comparing them requires the consideration of many parameters.

In addition, in order to compare energies we must be able to convert them to the same unit. This is the approach widely used in international statistics to evaluate energy resources at a global level, by country or by major energy player. The way these resources change is closely scrutinized, as a way of assessing the energy independence of a given country.

Chapter 1 described the different forms of energy and their level of technological and economic maturity. Chapter 2 presented the role of each of these solutions with respect to different energy uses.

In Chapter 4, we will take a look at how these solutions compare to one another. It will also be an opportunity to analyze how much they can be complementary in helping to achieve the world the decarbonization objective.

The comparison must take into consideration both their intrinsic properties (energy density, footprint, cost, decarbonization potential) and the constraints imposed by the operating modes of the energy system.

4.2 Characteristics of the various energy sources

Although they may provide an equivalent energy content, the various forms of energy have different characteristics (see chapters 1 and 2). **They are analyzed according to the following parameters:**

- a. **Energy density:** this is the amount of energy that can be produced with 1kg of the resource, if it is a fossil fuel or uranium (used for nuclear power generation), or the quantity of energy that can be produced on a given surface area (solar, wind, biomass,) or with a given volume

- b. **Abundance:** for fossil fuels, abundance is generally measured in years of future consumption, while bearing in mind that although this measure is very easily understandable, it is in fact complex because consumption trends are changing, with today's concern for energy efficiency in the Western world and the gradual decline of certain forms of energy such as coal for example. As for the resource, it depends on the exploration efforts and the cost of extracting it. If the expected market price is low compared to the cost of extraction, the resource will be left in the ground.

- c. **Availability:** this characteristic applies to the production of electricity. Intermittent energies like solar and wind energies are not available all the time. When their share in the electricity mix[124] becomes excessive, it poses a problem of balancing the grid. The grid must balance constantly the electricity demand, which is variable by nature (different quantities of electricity are consumed in summer and winter because of electric central-heating and air conditioning, for example), with electricity production. When the grid is no longer balanced, the security of electricity supply may be imperiled.

- d. **The impact on the environment:** this involves both land and water pollution and the emission of GHGs (carbon dioxide and methane) which contribute to global warming.

[124]The electricity mix is characterized by the percentage of the different forms of energy in the electricity production

ENERGY DENSITY

For the forms of energy which have a mass, the energy density is expressed in number of megajoules[125] per kilogram. The Figure 4.1 below compares the energy density of the main forms of energy :

- **Uranium** has a very high energy density. One kilo of natural uranium can generate as much electricity as 10 tonnes of oil consumed in a thermal power plant.[126]
- **Oil** also has a high energy density: one liter of fuel oil contains 10 kWh of energy, the same amount as one cubic meter (m^3) of natural gas[127] or the production of a 50 m^2 array of solar panels in one hour.[128]

In fact, for electricity, the energy density can be expressed in terms of quantity of energy per surface immobilized :

- **Solar** energy has a comparatively low energy density. In Bordeaux, 10 m^2 of solar panels only produce 4 kWh per day (the average daily electricity consumption of a household in France is 12.5 kWh). In France the roofs of an area equivalent to that of the city of Paris would have to be covered to generate the same amount of electrical power as a 1000 MW nuclear power station, and we must keep in mind that solar energy is intermittent. The energy produced depends on the hours of sunshine: in Morocco, the same amount of annual energy can be produced with twice as less surface.[129]

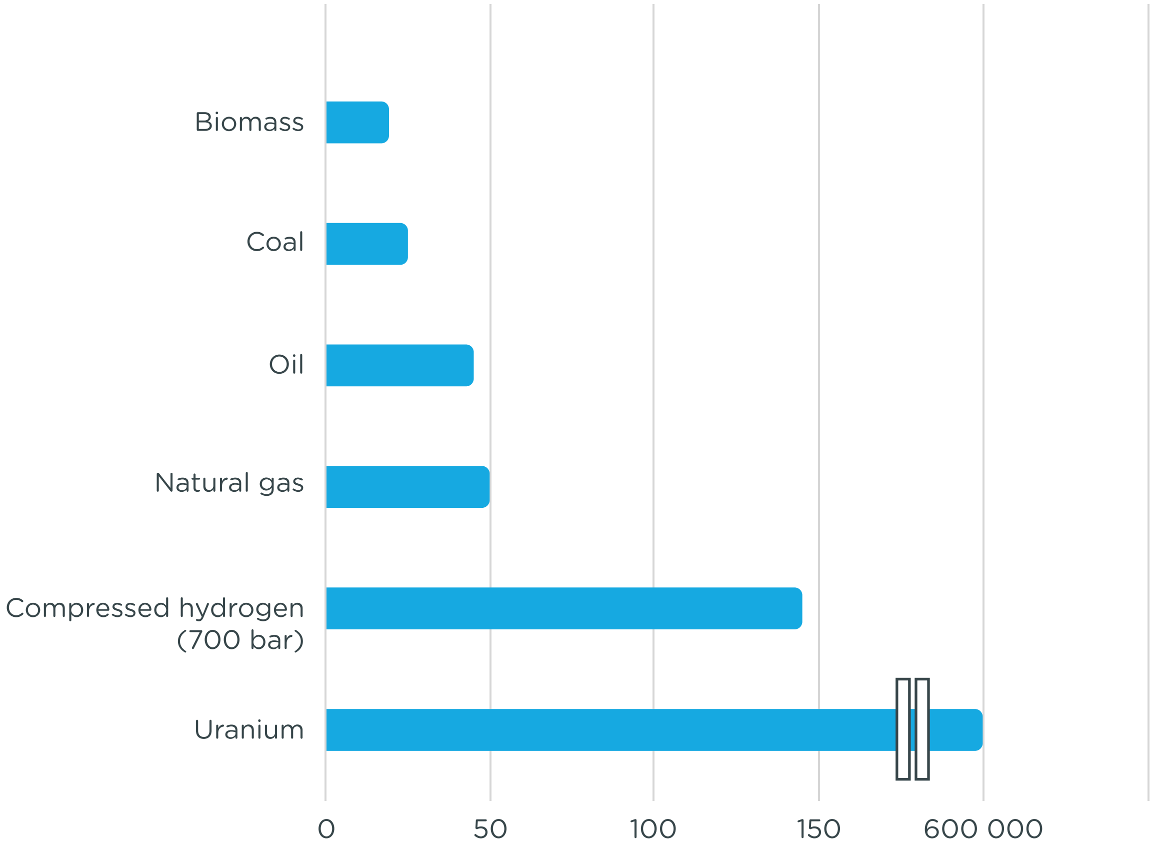


Figure 4.1: Energy density in Megajoules per kilogram for main forms of energy (MJ/kg)
Source : Capgemini Analysis
Please note that the graph does not include intermittent electricity which is final energy and has no mass.

[125]See definition of the joule unit in chapter 1
[126]https://cpdp.debatpublic.fr/cpdp-ppe/file/1562/reserves_uranium.pdf : 175 tons of natural uranium per year for 1000 MWel and an annual electricity production of 7 TWh.
[127]At standard pressure and temperature
[128]When the sky is clear and the sun shines perpendicular to its surface
[129]Capgemini analysis

AVAILABILITY AND IMPACT OF INTERMITTENCY ON ENERGY GRIDS

The electricity grid must be constantly balanced

Electricity has a major constraint compared to other forms of energy: the difficulty of storing it. At any given time, production must be equal to consumption, or the power grid will break down. The consequences of not effectively balancing the grid can be disastrous, as proved by the giant blackout of 2003 on the East Coast of the United States which cost the American economy 6 billion dollars.[130]

The grid operator is in charge of keeping this balance at all times by pulling in production plants, using storage facilities (especially hydro), importing electricity if necessary, and mobilizing (and remunerating) the various stakeholders likely to contribute to the balancing of the power grid[131]. Consumers can be mobilized either through tariffs that encourage them to consume less energy at times of peak demand, when balancing is most difficult (time of use tariffs)[132] or, in the event of days under great tension, through alerts (e.g. Ecowatt[133] in France) asking them to shift their consumption from peak hours to other times of the day. To encourage the development of load shedding, starting in 2021, the European Union will require electricity suppliers to offer at least one time-of-use tariff supply to their customers.[134]

In developed countries, electricity generation comes primarily from power plants running non-stop, or "base load" (nuclear, coal, run-of-river, cogeneration, gas) and peak load solutions (diesel, gas, hydraulic dams, batteries) that are brought in on an ad hoc basis for lengths of time varying from a few seconds to several hours. The increased share of intermittent renewable energies in the electricity mix makes this balancing more difficult. Electric cars charging is a new problem that grid operators will have to cope with.[135] However, we must admit that electric vehicles are also a potential means of massive electricity storage and could contribute to improving grid management if the grid is adapted accordingly.

In developing countries, where demand is often higher than the available electricity production, the operator uses load shedding methods, i.e. targeted power interruptions.

[130]Soult, F. (2003). EDF : chronique d'un désastre inéluctable (Documents, Actualités, Société) (French Edition) (0 éd.). CALMANN-LEVY.
[131]https://www.smartgrids-cre.fr/encyclopedie/la-flexibilite
[132]Dynamic Tariffs in Europe or Time of Use Tariffs in the US or Time of Use Tariffs aux Etats-Unis https://www.essentialenergy.com.au/-/media/Project/EssentialEnergy/Website/Files/Our-Network/TimeofUseBrochure.pdf
[133]https://www.monecowatt.fr/
[134]https://www.sia-partners.com/fr/actualites-et-publications/de-nos-experts/nouvelle-obligation-europeenne-doffre-tarification
[135]For a more detailed analysis of these grid balancing issues see the WEMO 2020 Global Editorial - https://www.capgemini.com/fr-fr/etudes/wemo2020/

Intermittency and load factor comparison by generation technology

Since the beginning of the 2010s, the share of renewable energies in the world's electricity production has increased significantly, thus creating new constraints for the grid:

- In times of overproduction, the means of storing electricity are limited, so as to avoid tripping the power lines, the grid operator can impose the reduction or disconnection of certain production means. This curtailment[136] is common practice in some regions where wind generation is often excessive.
- During periods of under-production, the grid operator must compensate for the imbalance using flexibility mechanisms (additional generation plants, load shedding, interconnections, storage). These alternative means of production called in as a back-up (gas-fired power plants, for example) cause the release of GHG emissions.

The capacity factor of an electrical production unit (e.g. a wind turbine) is the ratio between the energy it generates over a given period of time and the energy it would have produced in that same time if it had been running constantly at nominal power. For renewables, the load factor gives an indication of their intermittency: it is not chosen but imposed by the weather conditions. For other means of production, the load factor is chosen or controlled depending on whether it is of economic interest to run the plant or not. This is particularly the case for gas, which is very easy to control.

The table below shows the average load factors observed by technology around the world.

TECHNOLOGY	THEORETICAL LOAD FACTOR (BASELOAD)
Nuclear	>90%
Geothermal	80 - 90%
Biomass	70 - 80%
Hydropower	40 - 50%
Coal	70 - 80%
Natural gas	70 - 80%
Solar CSP	40 - 50%
Offshore wind	35 - 50%
Onshore wind	20 - 35%
Solar PV	12 - 20%

Figure 4.2: Comparison of load factors by power generation technology
Source : IRENA, US DOE, IEA

[136] https://physicsworld.com/a/curtailment-losing-green-power/

The load factor is constantly changing for all technologies depending on many parameters: weather conditions, demand level, equipment availability, maintenance period. **Here are some examples of the link between weather conditions and electricity generation levels:**

- Wind power generation is higher in winter, which helps in countries dependent on electric heating,
- Drought episodes lead to a decrease in hydroelectric production (e.g. Brazil) and in the production of nuclear power plants along the river banks,[137]
- In Germany, the circulation of coal barges depends on the navigability of the rivers, and the production of coal-fired power plants can be interrupted due to lack of supply.[138]

The load factors must be considered when various power generation technologies are combined. The availability of solar power plants (which do not run at night) must be backed by the availability of a flexible nuclear or gas power plant - unless huge storage solutions are added.

These considerations are essential to take into account, all the more so when considering that the energy produced supplies indispensable and critical areas such as the medical sector, which cannot run on an intermittent supply.

[137]https://www.irsn.fr/FR/connaissances/Installations_nucleaires/Les-centrales-nucleaires/impact-secheresse-centrale/Pages/Impact-secheresse-fonctionnement-centrales.aspx#.YG8jxK8zY2w
[138]https://www.montelnews.com/en/story/coal-barges-face-rhine-closures-as-river-levels-swell/1190401

4.3

How to compare the energy costs of various types of energy?

Comparing energy costs makes sense when comparing energies that serve the same end use. For example, we can compare the cost per 100 km while driving an internal combustion engine vehicle and an electric vehicle, or compare two sources of electricity, after making sure they are comparable in terms of availability (load factor).

However, thanks to the conventions for converting secondary energy into primary energy explained in the section "Going further", it is possible to make a (notional) comparison of energies in megajoules and in cost.

COMPARISON OF AVERAGE COSTS OF ELECTRICITY PRODUCTION

The costs associated with the various means of electricity generation are very different. To compare them, it is necessary to consider the rate of expenditure over time, the lifespan and the amount of electricity produced, which depends on the load factor. For example, nuclear reactors take a long time to build and require very large investments but have a relatively low cost of fuel. The opposite applies to fossil fuel power plants where the investment is lower but the fuel cost is higher. For renewable energy, the fuel is free but there is a significant initial investment cost.

Economists and engineers who develop projects have long used the concept of discounting, which allows them to evaluate a good or a service at various points in time. It is based on an annual discount rate[139] that takes into account the capital cost and the risks incurred. The calculation of the cost of production is very sensitive to the discount rate used, generally between 5 and 10%.

Thus, to compare the cost of electricity produced by these different sources, the cost of production throughout the life of the plant (construction cost, fuel cost, maintenance cost, etc.) is evaluated, and these costs are discounted.

These discounted costs are then divided by the quantities of electricity produced during the life of the plant, also discounted.[140] This is the method referred to as the Levelized Cost Of Electricity (LCOE) expressed in €/kWh.

[139]The discount rate is used to discount a future flow and calculate its equivalent present value. Thus 100€ in 2020 will have a different equivalent value because of the discount rate. This rate depends on inflation, the level of risk, the cost of debt and the cost of capital

[140]https://www.connaissancedesenergies.org/quest-ce-que-le-lcoe-170908

The results obtained are described in graph 4.3. Nevertheless, this remains very much a matter of theory and it is not fully sufficient for comparison because it does not reflect all external factors (storage cost for renewables, cost of reinforcing networks, end-of-life cost for nuclear, impact on biodiversity and landscapes) nor the fact that production can be adjusted to demand in real timel[141]. There is no actual way to directly compare a MWh produced by a controllable means of production (gas, coal, nuclear, hydro) with a MWh of production whose availability depends on external and non-controllable factors (e.g. wind, photovoltaic).

Furthermore, the LCOE analysis below does not consider the additional cost of carbon prices (either due to tax or to the purchase of emission allowances), which only impacts coal and gas-fired generation. For example, if we take the current ETS price of €50/tCO_2[142] then the LCOE would increase by about €50/MWh for coal and €22 / MWh for gas.

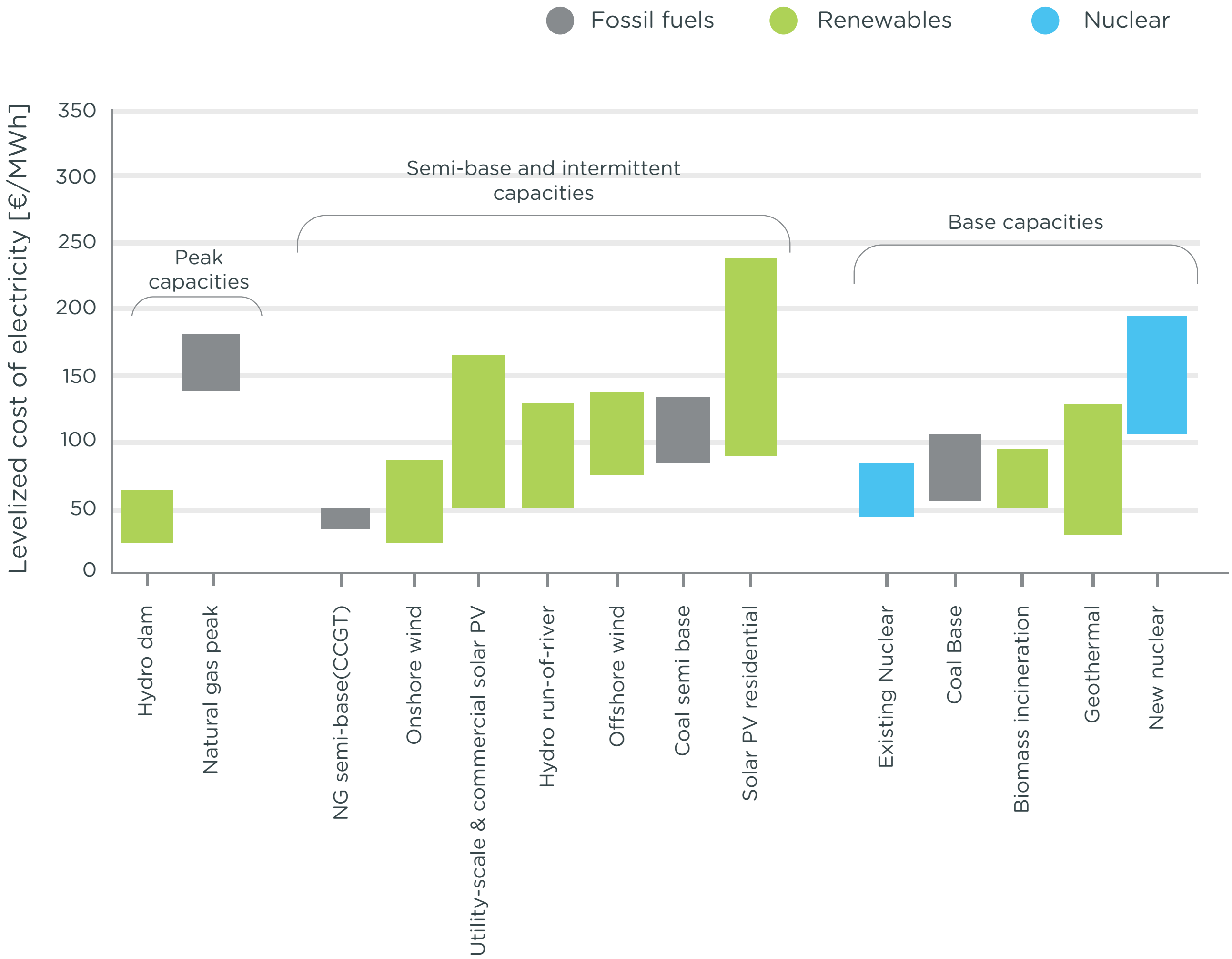


Figure 4.3: Discounted average electricity costs for 2019 in Europe (excluding carbon prices)
Source : Capgemini WEMO 2020

[141]According to the economists Stefan Ambec and Claude Crampes of the Toulouse School of Economics, it is not a question of comparing the MWh produced but the MWh delivered in a given place at a given date. https://www.latribune.fr/opinions/tribunes/les-couts-lisses-de-l-electricite-774441.html?amp=1&__twitter_impression=true
[142]https://www.bloomberg.com/news/articles/2021-05-13/germany-signals-record-eu-carbon-price-rally-may-slow-down

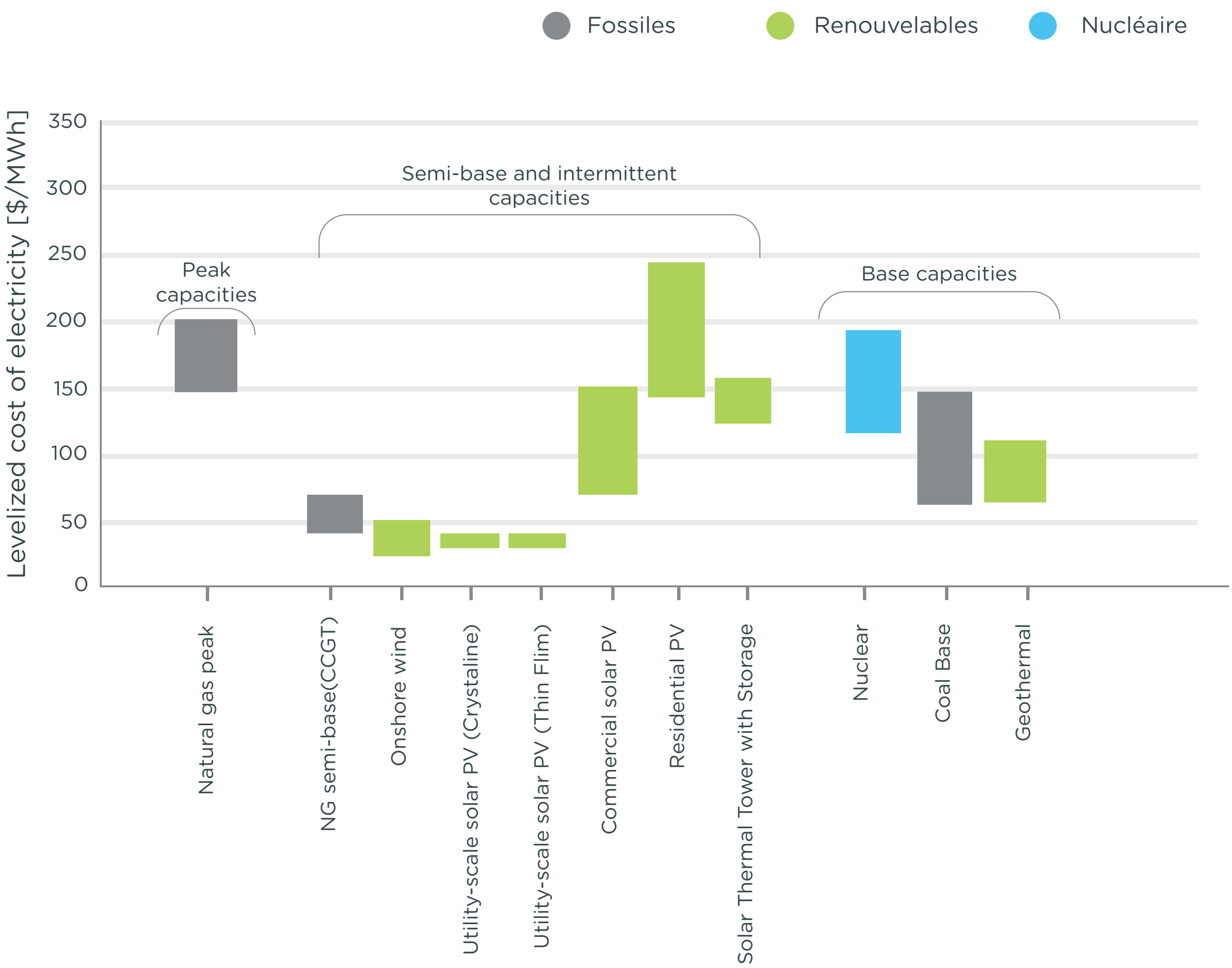


Figure 4.4: Discounted average cost of electricity in the US in 2019 (excluding carbon price)
Source : Capgemini WEMO 2020

Notes: Gas-fired power plants operate differently depending on market conditions and generation technologies. The term "peak" refers to operation for a few weeks or days per year, which corresponds to an effective load factor of 10-20%. In countries with high renewable electricity production like the UK, gas-fired power plants do not operate continuously and are referred to as "semi-base", which corresponds to an effective load factor of 50-60% vs. a theoretical load factor of 85%. On average, gas-fired combined cycle power plants in Europe operate at about 40-50% due to market conditions, according to BNEF data.

COMPARISON OF ENERGY COSTS FOR OVERLAND TRANSPORT

Comparing costs in the case of vehicle transportation is complex because all stages from energy production to energy use must be considered. The number of transformations and the efficiency at each transformation stage will play a decisive role in understanding the cost.

There are very few transformation steps in the case of an all-electric vehicle, which is why the overall efficiency from production to use is higher than that of the hydrogen vehicle. According to a study by the British think tank and campaign group, Transport & Environment UK (T&E), the efficiency is 73% for an electric vehicle compared to 22% for a vehicle running on a fuel cell, and 13% for a vehicle using a synthetic fuel (see chapter 2 on the description of the types of fuels). In the case of a vehicle powered by an internal combustion engine running on gasoline or diesel, the efficiency is in the range of 26 to 42%[143]

For example, the total lifetime cost (purchase, fuel, and maintenance costs) of a fuel cell truck in 2030 is estimated by T&E to be €459,000 compared to €393,000 for an electric vehicle.

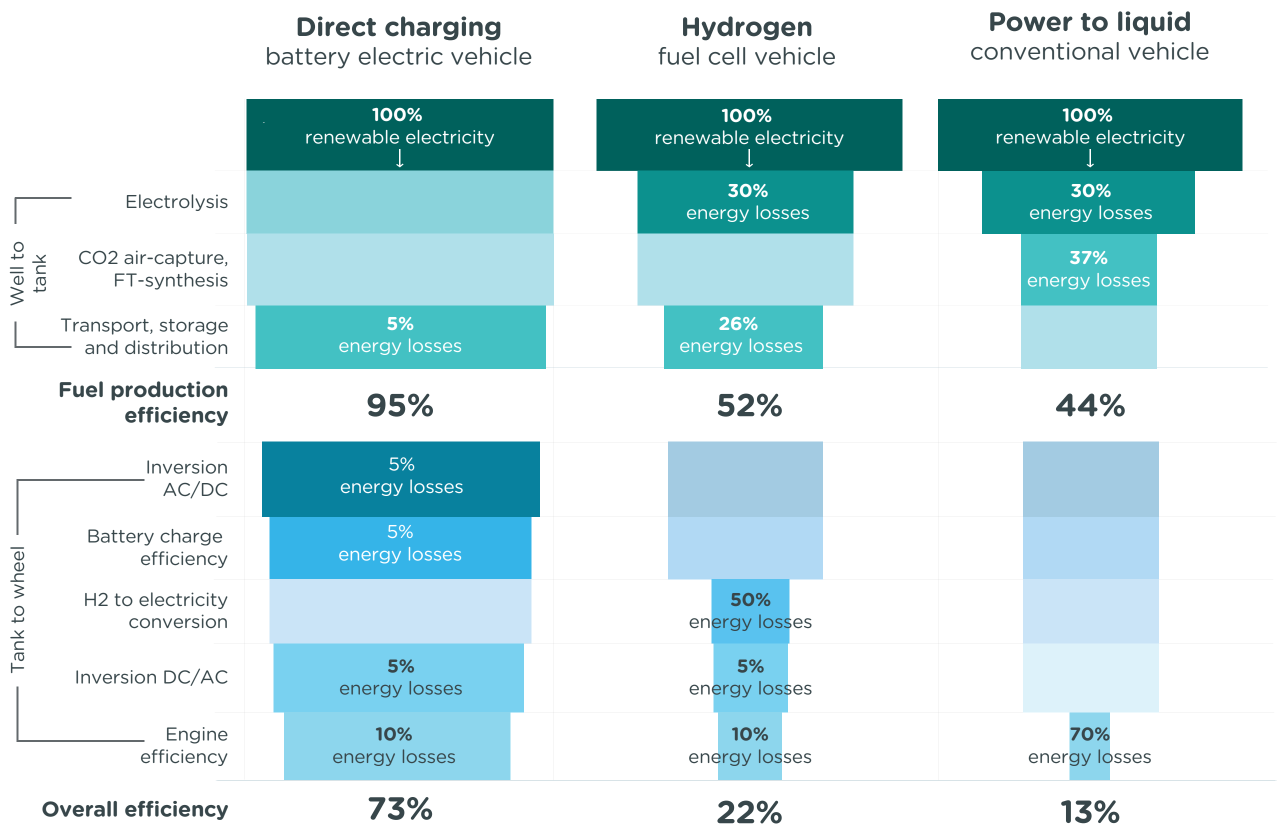


Figure 4.5: Comparison of vehicle performance: electric vehicle, hydrogen vehicle and synthetic fuel vehicle
Source : British think tank and campaign group "Transport & Environment UK"

Note : The efficiency for a thermal vehicle is about 36 to 42% in optimal conditions and is reduced to 15% in built-up areas

[143]https://www.ifpenergiesnouvelles.fr/enjeux-et-prospective/decryptages/transports/les-vehicules-essence-et-diesel

TO GO FURTHER - WHAT ARE THE METHODOLOGIES TO CONVERT ENERGY SOURCES HAVING DIFFERENT PROPERTIES AND UNITS OF MEASUREMENT?

There are two main methods that can be used to calculate the primary energy equivalent of energy sources for an entire country: the method known as the partial substitution method, and the physical energy content method. The share of renewables in the total energy supply will appear as being different depending on the method used because these energies differ in the treatment of electricity from solar, hydro, wind, etc. It is therefore important to understand the underlying conventions that have been used to calculate the primary energy balances.

The partial substitution method

This method assesses the amount of energy that would have to be imported or produced in the form of fossil fuels or mining (uranium) if all consumption or production were in this form. Typically, for electricity, it calculates the quantity of primary fossil energy that would be necessary to produce the same quantity of electricity in conventional thermal power plants (hence the name of substitution method). The amount of final electricity is therefore divided by R, the average efficiency of fossil fuel power plants,[144] or, in other words, it is multiplied by 1/R (conversion factor).

This method has some limitations, including the difficulty of choosing an appropriate efficiency that does not appear too arbitrary, the fact that this method is not relevant for countries with a high share of hydroelectricity, and that it will be less and less relevant given the increase in the energy mix of renewable energies such as wind and solar electricity.

However, it continues to be used by the U.S. Energy Information Administration (EIA) with a thermal conversion coefficient based on an R-value of around 40% and therefore a 1/R conversion factor of around 2.5.

But this thermal conversion coefficient is not used for the direct consumption of some of these renewable energies such as solar thermal energy used to produce domestic hot water or geothermal energy to produce electricity.

[144] See Chapter 1

The physical energy content method

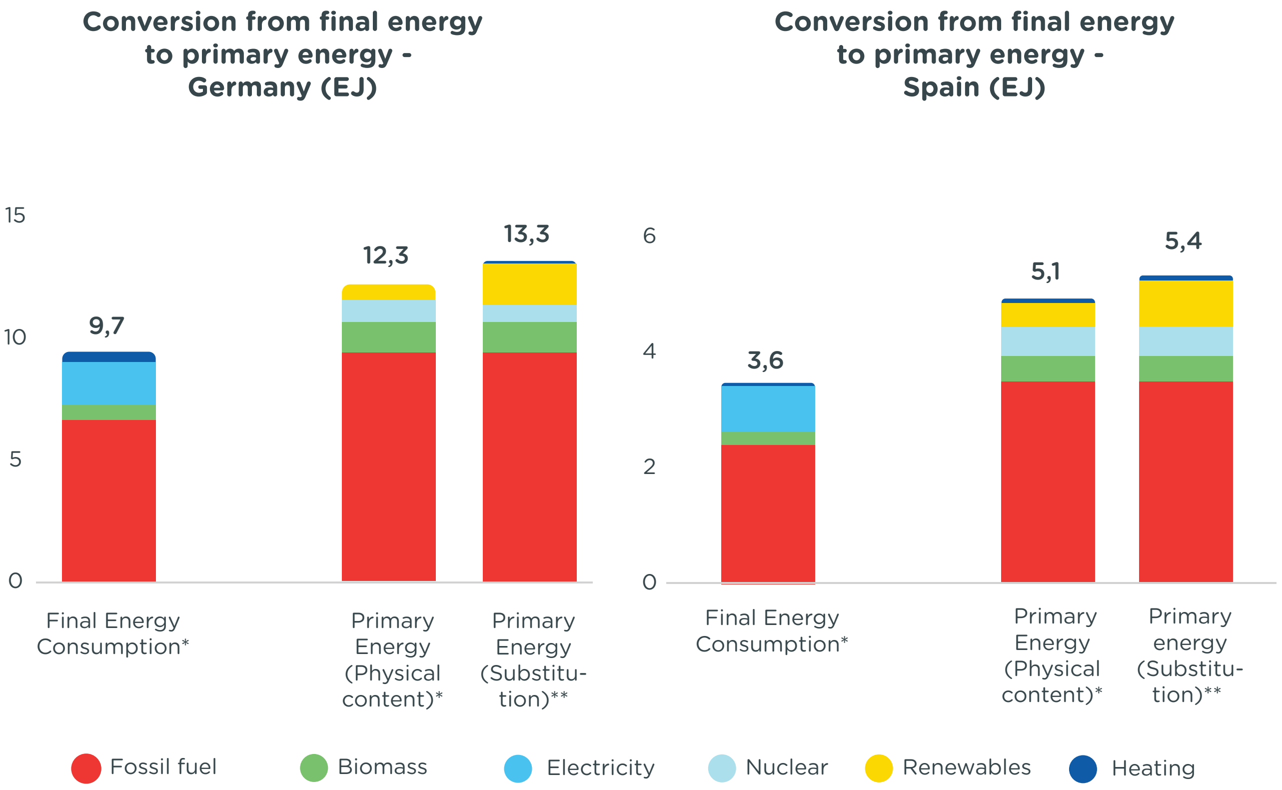
To take into consideration the growing importance of renewable energy, the IEA, like most European organizations, has adopted the physical energy content method.

This method, which is closer to physical reality, considers that electricity from renewable sources is primary energy. Electricity is indeed directly produced by natural elements such as wind, sun, or waterfalls. It is equivalent to using a conversion coefficient of 1 (or 100%). In the case of nuclear electricity production, which uses heat energy, the IEA uses a conversion coefficient of 3, which corresponds to an efficiency of 33%, the average efficiency of nuclear power plants in Europe.

These two methods are summarized in the table below:

	Physical energy content	Partial substitution
Methodology	Electricity brought back in primary energy with a different conversion factor according to whether the electrons are considered as a primary or secondary source. Electrons considered as primary energy - hydro: 100% efficiency - solar PV: 100% efficiency - wind: 100% efficiency **1 TWh of these renewable energies will count as 1 TWh of primary energy or 86 kToe** Electrons considered as secondary energy - Nuclear: 33% efficiency - Concentrated solar power for electricity: 33% efficiency - Geothermal for electricity: 10% efficiency - CCGT combined cycle gas: 60% efficiency **1 TWh of nuclear or concentrated solar electricity will count as 3 TWh of primary energy or 258 kToe**	Electricity converted into fossil energy that would be required to produce an equivalent quantity of electricity, whatever it may be. We use the average efficiency of a thermal power plant, often around 40% (and which changes over time). 1 TWh of electricity corresponds to 2.5 TWh of primary energy or 215 kToe.
Examples of applications	- IEA, OECD - Many organizations using IEA data	- US EIA (yield = 38% for Wind, Solar, Hydro, Geothermal, 33% for Nuclear) - BP (BP Statistical Review and International Comparisons): yield = 40% (2019) ⟶ 45% (2020-2050)

Figure 4.6: Methods of energy conversion
Source : IEA, BP Statistical Review of the World Energy, US EIA



*IEA data
**Renewables converted with a 40% factor

Figure 4.7: Examples of primary energy conversion rates for Germany and Spain
Source : IEA data for final consumption and primary energy (physical content)
Note: The volume of primary energy by substitution has been reconstituted with conversion factors of 40% for renewable energies and nuclear power.

4.4 Synthesis

The various forms of energy, whether primary energy (fossil, nuclear, hydraulic, biomass, solar, wind) or secondary energy (electricity, hydrogen, e-fuels, etc.) all have different characteristics and uses that need to be clearly understood to be able to compare them in a fair and relevant way.

Successfully decarbonizing the energy system also means allowing for flexibility needs and assembling solutions (production, storage, demand management) to best meet the various energy needs. In the future, flexibility could be reinforced by links with gas and heat networks, for example by using surplus electricity to produce hydrogen which will then be injected into the gas network (this is called Power-to-Gas or Power-to-X). However, the more transformation steps there are, the more losses there are and the higher the final cost.

The table below summarizes all the characteristics to be taken into consideration to compare the various energies between one another.

	Oil	Natural Gas	Coal	Biomass	Uranium / Nuclear	Hydro dams	Solar PV	Solar CSP	Onshore wind	Offshore wind	Hydrogen (vector)	Electricity (vector)
Energy density (MJ / kg)	Very high (41-48 MJ/kg)	High (38-50 MJ/kg)	High (24 MJ/ kg)	Medium (12-19 MJ/kg)	Extremely high (600 000 MJ/kg of uranium)	High (efficiency: 70 à 80%)	Very low (circa. 1,4 MJ/m2/d in Mid-Europe): efficiency: 2 to 18%	Very low (circa. 4 MJ/m2/d in Mid-Europe): efficiency: 35% to 40%	Low (circa. 72 MJ/m2/d): efficiency: 23 to 25%	Low (circa. 115 MJ/m2/d) efficienccy: 38%	Very high (compress-ed at 700 bar)	N/A
Abundance	60 years of consump-tion (including shale oil)	80 years of consump-tion (including shale gas)	135 years of consump-tion	High (10-25% of current energy consump-tion)	135-160 years of consump-tion	Limited by topo-graphy	Infinite (limited by available space)	Infinite (limited by available space)	Infinite (limited by available space)	Infinite (limited by available space)	Limitation: amount of gas or electricity for its production	N/A
Negative imp-acts / electri-cal networks	No	No	No	No	No	No, can be used as energy storage	Yes, need for predictable energy and storage	Yes, but has some storage	Yes, need for predictable energy and storage	Yes, need for predictable energy and storage	No	N/A
Negative imp-acts on the environment	CO_2/CH_4 emissions	CO_2/CH_4 emissions	CO_2/CH_4 NO_x/SO_x emissions	Emission of fine particles, CO_2/CO/ NO_x/SO_x	Radioac-tive waste	Modifica-tion of local hydrauli-city	Low	Low	Low	Low	Grey H_2 : CO_2 (+++) Blue H_2 : CO_2 (+) Green H_2 : none	N/A
Corrective measures	Carbon Capture, Use and Storage (CCUS)	Carbon Capture, Use and Storage CCUS	Carbon Capture, Use and Storage (CCUS); Fluidized bed boiler	luidized bed boiler	Vitrifica-tion waste, Reversible deep storage	N/A	N/A	N/A	N/A	N/A	N/A	Enhancing energy efficiency

Figure 4.8: Synthesis of energy source characteristics
Source : Capgemini Analysis

The diagrams below illustrate the orders of magnitude of installed power, costs, surface area and number of installations to produce 22 TWh of final energy in the form of electricity or hydrogen.

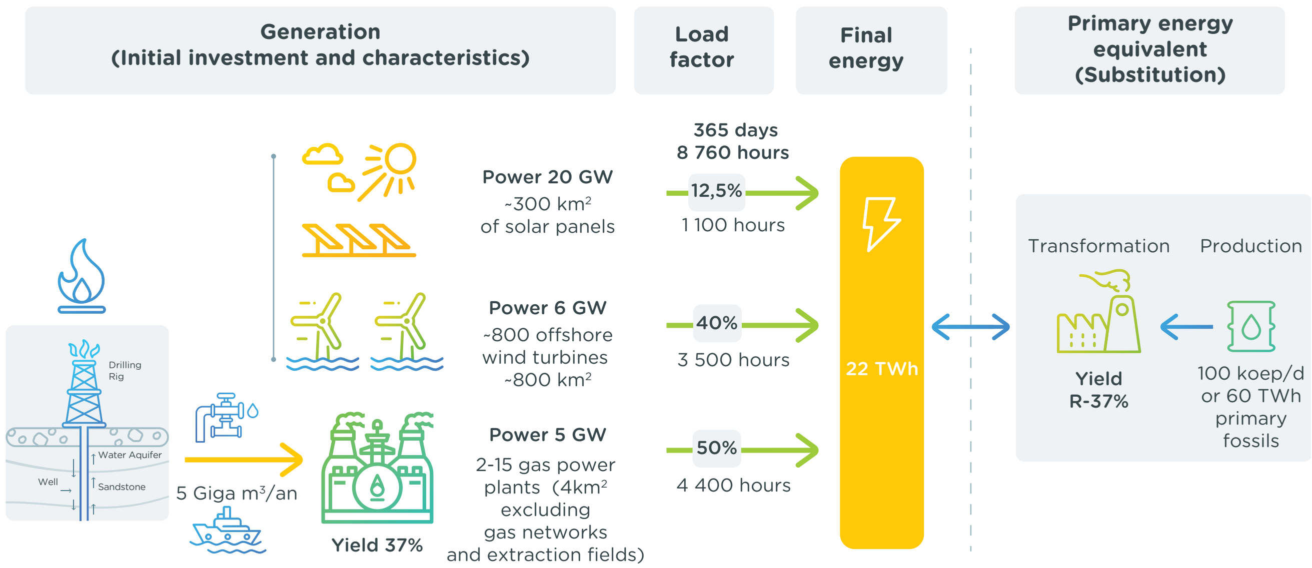


Figure 4.9: Comparative electricity generation of 22 TWh: solar photovoltaic, offshore wind and gas
Source : Capgemini Analysis

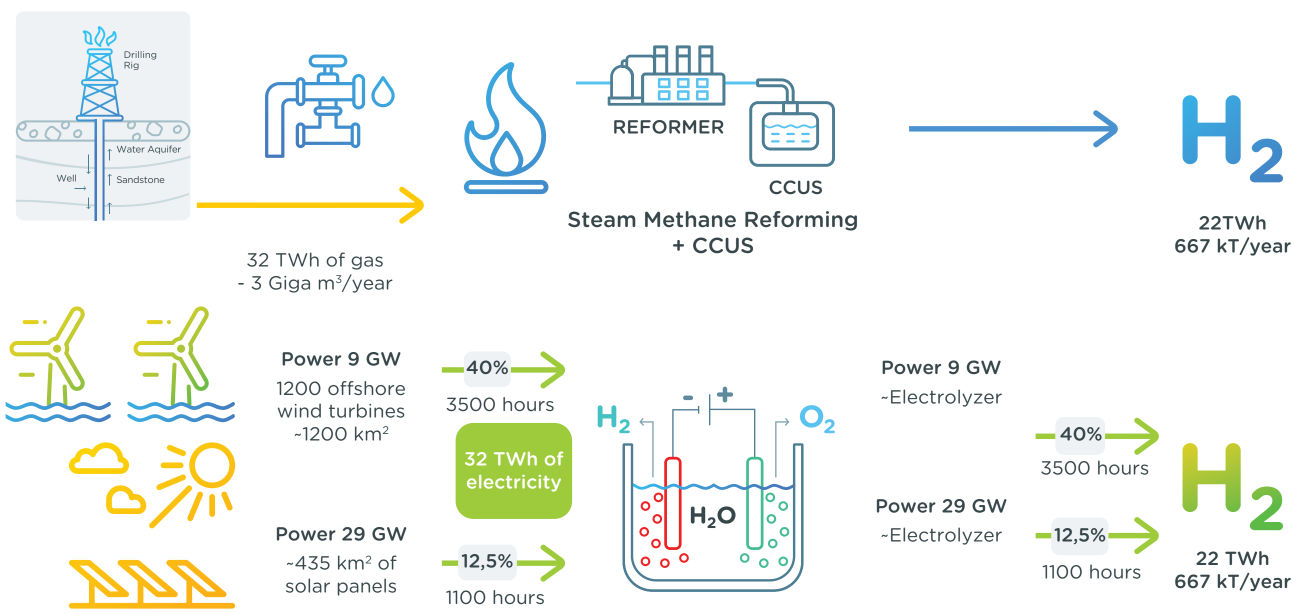


Figure 4.10: Comparison of hydrogen production: blue hydrogen vs. green hydrogen
Source : Capgemini Analysis

5

How to ensure energy supply while decarbonizing the economy ?

5.1 Levers for action: avoid, reduce, compensate

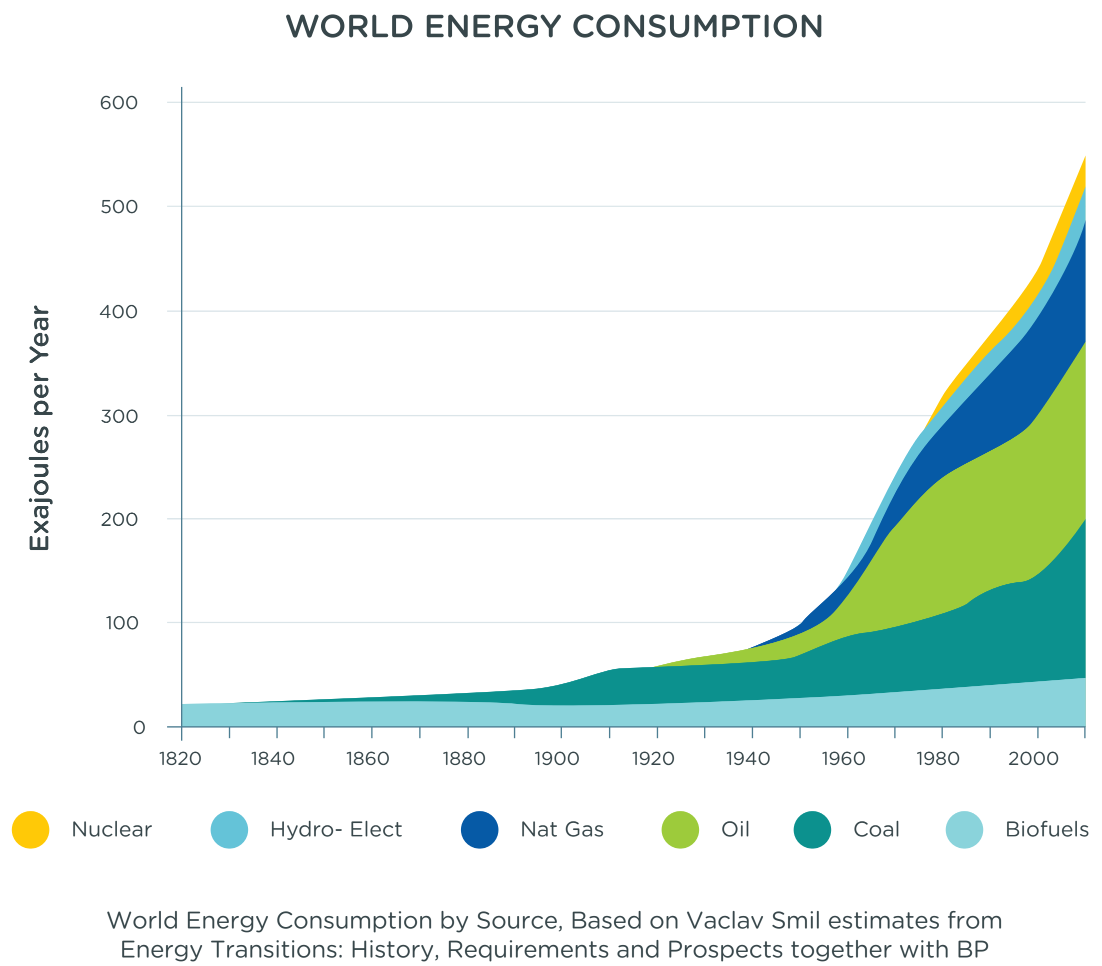


Figure 5.1: World energy consumption since 1820 in EJ
Source : Vaclav Smil & BP Statistical 2020

Energy is fundamental to human life on Earth and for the well-being of populations.

Since the industrial revolution, we have witnessed a very strong growth in the demand for energy linked to the growth of the population and the improvement of living standards. This strong growth in demand, which was mainly driven by fossil fuels, mechanically increased GHG emissions.[145]

At the Earth Summit organized by the United Nations in Rio de Janeiro in 1992,[146] the 189 countries present adopted a founding text of 27 principles, entitled "Rio Declaration on Environment and Development", which defines the concept of sustainable development and states that, to achieve it, "environmental protection must be an integral part of the development process and cannot be considered in isolation" (Principle 4). It should also be noted that among the 17 Sustainable Development Goals of the United Nations[147] are clean and affordable energy (Goal 7) and the fight against climate change (Goal 13).

In 2015, the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP 21)[148], which was held in Paris, adopted the Paris Agreement, under which the States Parties set themselves the objective of limiting the increase in the temperature of our planet to less than 2°C compared to pre-industrial levels, with a further ambition to limit warming to 1.5°C[149], and of achieving carbon neutrality during the second half of the 21st century.[150] This implies a limitation of GHG emissions and their compensation on a global scale.

[145]Except in 2020, a year marked by the Covid-19 pandemic, during which energy consumption decreased by 5% and GHG emissions by 7%.
[146]https://www.un.org/fr/conferences/environment/rio1992
[147]https://www.un.org/sustainabledevelopment/fr/objectifs-de-developpement-durable/
[148]https://unfccc.int/fr/process-and-meetings/l-accord-de-paris/qu-est-ce-que-l-accord-de-paris
[149]Paris Agreement, Article 2, 1, a)
[150]Paris Agreement, Article 4, 1.

Unfortunately, since 2015, (except for 2020), global energy consumption and GHG emissions have continued to rise, particularly driven by developing countries.[151]

According to a special IPCC[152] report published in 2018 related to the 1.5° scenario, the level of international ambition (resulting at that time from Nationally Determined Contributions) **is insufficient to limit** warming to 1.5°C. The next IPCC assessment report due in 2022 is strongly expected to address this topic.

Again according to the IPCC, without a more drastic and urgent temperature limitation ambition in the coming years, bringing about a major decrease of GHG emissions by 2030, global warming will exceed 1.5°C in the coming decades, leading to an irreversible loss of the most fragile ecosystems, and to repeated climatic events that will be very damaging to the most vulnerable people and societies.

As we have already described, energy and climate are linked, and so are energy and development. Among the 17 United Nations Sustainable Development[153] Goals are clean and affordable energy and the fight against climate change.

The question that arises is: **how do we ensure the planet's energy supply without increasing its temperature and, moreover, without depleting its resources?**

To meet this twofold challenge, many means and avenues are envisaged.

They consist in:

- **Avoiding** unnecessary uses and using technologies that do not emit GHGs
- **Reducing** emissions and energy losses by increasing the efficiency of techniques and processes,
- **Compensating** by facilitating the removal of carbon from the atmosphere. This lever consisting of sequestering it in carbon sinks by natural or technical means must be activated on the remaining share of the emissions once the maximum efforts have been made to Avoid and Reduce GHG emissions.

CARBON NEUTRALITY

According to the Paris Agreement, it is necessary to achieve carbon neutrality in the second half of the 21st century so as to contain the rise in the average temperature of the planet, and keep it well below 2 degrees. Carbon neutrality corresponds to the balance between GHG emissions and absorptions by carbon sinks. It is also referred to as "net zero emissions". More and more states as well as the European Union cities and companies have chosen to aim for carbon neutrality as early as 2050.

REINVENTING AND ACCELERATING THE DEVELOPMENT OF A DIVERSIFISED AND DECARBONISED ENERGY MIX

Fossil fuels that emit CO_2 still represent more than 80% of the world's energy consumption. **To move towards carbon neutrality, we must:**

1. Accelerate the substitution of fossil fuels with decarbonized energies. This acceleration is important because the penetration

[151]See chapter 2 concerning energy demand
[152]IPCC, 2018: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,sustainable development, and efforts to eradicate overty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock,M. Tignor, and T. Waterfield (eds.)]. In Press.
[153]https://www.un.org/sustainabledevelopment/fr/objectifs-de-developpement-durable/
[154]Rare metals such as nickel or rare earth

of new technologies is slow. Possible actions include:

- Further electrification (electric vehicles, industrial processes, heating) through low-carbon power generation,
- Incorporation of sustainable liquids or gases (bioenergy, hydrogen) into oil and gas to reduce their carbon footprint,
- The use of synthetic fuels or gases.

2. For residual emissions, capture and neutralization are necessary: generalize CO_2 capture and storage (CCS) in industrial facilities and power plants. As the costs of current technologies are still too high compared to the cost of carbon (e.g. the cost of ETS markets, see below), it is important to accelerate the research, development and deployment of CCS technologies and also to develop nature-based solutions. In parallel, the cost of carbon must be increased (see below)

INVESTING IN ENERGY EFFICIENCY

Incentives and education policies can continuously improve energy efficiency, especially in developing countries, to produce the same goods and services while using less energy. For example, LED bulbs produce the same amount of light as incandescent bulbs using 75-80% less electricity.

However, the rate of reduction in global energy intensity seen in recent years (1.6% in 2019 and 1.5% in 2018)[155] is far below the level needed to meet global climate goals. The IEA's NZE report[156] assumes an acceleration of this reduction with an energy efficiency of 4% per year between 2020 and 2030, which is very ambitious compared to the observed average of 1.6% between 2010 and 2020.

In some countries, such as France, the obligation for energy suppliers of a certain size to acquire CEEs "*Certificats d'Economie d'Energie*", or energy saving certificates[157] by encouraging their customers to make energy savings is a costly but effective mechanism for these companies.

ADAPTING ENERGY SOURCES TO DIFFERENT USES

In the past, energies have been adapted to end uses. Indeed, given the technological progress and the evolution of end uses, the type of energy adapted to each end use has evolved. For example, electricity is mainly used for lighting and stationary engines, whereas coal gas was used throughout the 19th century for street lighting in Western countries.[158]

The response to the climate challenge also involves adapting energies to end uses, this time favoring decarbonized solutions. For each use, the choice must be for the most suitable form of decarbonized energy, which is readily available and requires the least amount of transformation, so as to limit losses and costs.

Electricity is the best energy carrier for many end uses because it requires only one transformation and is easily transported. It is used for many purposes, unlike heating networks, which are more efficient but only for central-heating purposes. Hydrogen, which requires two transformations, and even more so synthetic fuels, which require three transformations, should be directed towards end uses that cannot be decarbonized otherwise.

ACCELERATING TECHNOLOGICAL PROGRESS

Involving ambitious research and development policies, **the acceleration of technological progress plays an essential role.**

Technologies in each sector

- In the short term: for example, the use of semiconductors with higher photon-electron conversion efficiency to continue to lower the cost of photovoltaic solar energy or the use of carbon nanotubes to improve the performance of batteries.[159]
- In the medium term: for example, the technology of high-temperature electrolyzers, developed by the CEA[160] promises high yields in the production of electrolytic hydrogen
- In the long term: research on nuclear fusion, in particular the international ITER project[161], could lead to the industrial production of carbon-free electricity four times greater than that of nuclear fission, using widely available and virtually inexhaustible fuels.

[155]Source: IEA (International Energy Agency) (2020) Energy Efficiency 2020. https://www.iea.org/reports/energy-efficiency-2020 All rights reserved.
[156]Source: IEA (International Energy Agency) (2020) Energy Efficiency 2020. https://www.iea.org/reports/energy-efficiency-2020. All rights reserved.
[157]https://www.ademe.fr/expertises/changement-climatique/passer-a-laction/comment-valoriser-economies-denergie-cee/principes-fonctionnement-dispositif-cee
[158]http://sii-technologie.ac-rouen.fr/Microtechniques/STI2D/Projet_Lumea/Pour_aller_plus_loin/Histoire_de_l_eclairage_en_France.pdf
[159]http://www.nawatechnologies.com/nawa-technologies-revolutionne-stockage-de-lenergie-nouvelles-batteries/
[160]https://www.industrie-techno.com/article/la-technologie-d-electrolyse-du-cea-qu-exploitera-genvia-pour-produire-de-l-hydrogene-atteint-99-de-rendement-se-rejouit-julie-mougin-du-cea-liten.63839
[161]https://www.iter.org/fr/accueil

Using digital with the generalization of connected sensors, data analysis and artificial intelligence

- For example, to better understand the local wind and better use it to produce electricity.
- On the practical use side, domestic sensors controlled remotely by a cell phone allow the energy consumption of homes to be reduced while keeping the same level of comfort.

REINFORCING AND CREATING CARBON SINKS TO REACH NET ZERO OBJECTIVES (OR CARBON NEUTRALITY)[162] :

Achieving carbon neutrality by the second half of the century requires drastic actions to reduce emissions from human activities from 40 to 70% to limit warming to 1.5° C by 2050[163] This will also require eliminating residual GHG emissions by removing them from the atmosphere and sequestering them.

The steps to do this could be:

- Increasing natural carbon sinks ("Nature Based Carbon Removals" in English)
- Implementing carbon sinks using artificial processes to remove CO_2 in large quantities. These actions are grouped under the name of CO_2 Carbon Capture and Storage (CCS).

CO_2 capture consists of trapping the carbon dioxide molecules before, during or after the combustion stage to prevent their release into the atmosphere. This process reduces the efficiency of the installations, making its cost significant.

This capture method can be implemented in industries that emit a large amount of CO_2: power plants that run on coal, fuel oil or even gas, steel or petrochemical plants, cement factories, oil refineries, etc.

After the capture phase, the carbon dioxide must be transported to a permanent storage site and then injected into the subsoil or into old oil wells at sea, for example. The characteristics of the storage facilities chosen must allow the CO_2 to be kept captive for thousands of years. These facilities need to be monitored continuously.

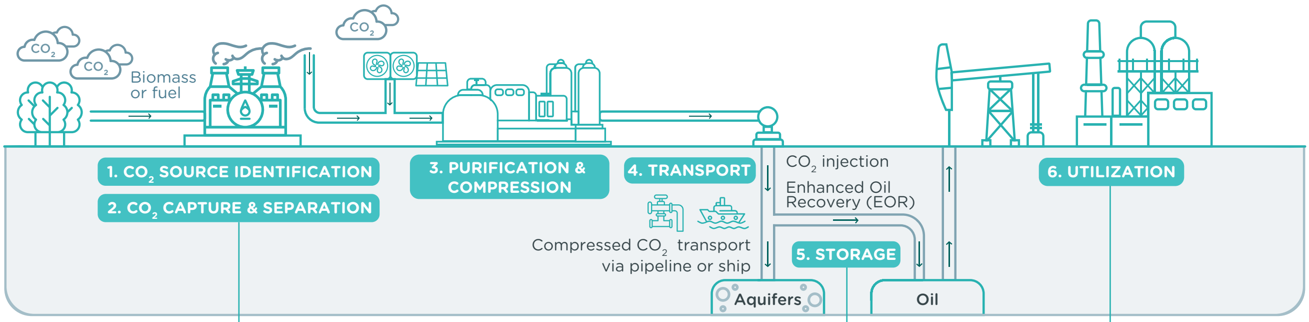
The captured CO_2 can also be reused (CCU Carbon Capture & Usage), for example combined with green hydrogen to produce fuels and synthetic gases.

Major efforts in research and development and the construction of prototype facilities have been underway for many years[164]. The aim is to lower the cost of the CCS process, which is currently close to €100/tCO_2[165]. According to the UNECE, in Europe alone, approximately €320 billion will be needed to deploy CCS solutions and an additional €50 billion to finance transport infrastructure.[166]

[162]https://www.europarl.europa.eu/news/fr/headlines/society/20190926STO62270/qu-est-ce-que-la-neutralite-carbone-et-comment-l-atteindre-d-ici-2050
[163]IPCC, 2018: Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. In Press.
[164]https://totalenergies.com/group/commitment/climate-change/carbon-neutrality
[165]This is the case of the "Northern Lights" project in Norway. Of course, the economic model of such installations improves as soon as a high carbon cost is introduced.
[166]https://news.un.org/en/story/2021/03/1086312

CARBON CAPTURE, USE AND STRORAGE (CCUS)

CCUS (Carbon Capture, Utilization and Storage) is essential to unlock the full potential of decarbonization and attain carbon neutrality

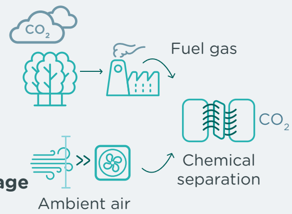


Point Source of CO_2 in Industry

CO_2 from industries (cement, steel),hydrogen production from fossil fuels, or power generation is captured before it reaches the atmosphere and is then compressed and injected into porous rock layers.

Biomass Energy with Carbon Capture and Storage (BECCS)

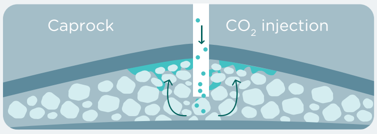
Direct Air Carbon Capture and Storage (DACCS)



Net negative emissions technologies are key to reach net-zero and then net negative emissions. In BECCS, CO_2 is taken out of the atmosphere by vegetation, then recovered from the combustion products when the biomass is burnt. In DACCS, CO_2 is captured directly from the air.

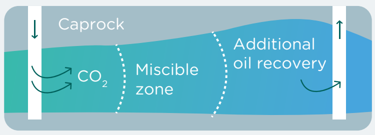
Aquifers for Sequestration of CO_2

Aquifers are geological formations containing brine in porous rock at depths over 1km CO_2 can be pumped down into the rock for sequestration.



Enhanced Oil Recovery (EOR)

EOR is a family of techniques that increases the recovery of oil and gas while storing CO_2. Dependent on operational choices, the volume of CO_2 stored could exceed the CO_2 content of the produced hydro-carbons.



Solutions for Carbon Utilization

Carbon utilization can unlock the commerciality of CCUS projects for the industrial, steel, cement and chemical sectors. CO_2 captured can be used as a feedstock to produce a range of products, such as concrete, methanol, ethanol, carbonates, plastics etc.

Awareness
Recognise CCUS as a viable climate mitigation option and consider it when developing national plans.

Acceptance
Develop and integrate policies to allow full commercialisation of CCUS technologies.

Finance
Create a funding mechanism for CCUS and direct investments towards modernization of energy infrastructure.

Figure 5.2: Carbon capture, use and storage

Source : United Nations Economic Commission for Europe (UNECE)

MEASUREMENT

Measurement is essential for comparing energies and tracking progress.

- In Chapter 4, we described the methods for **comparing various types of energy.** Even if these methods do not take into account the different characteristics of these energies, they are important as a way of comparing, monitoring and managing energy portfolios (of energy providers or countries).
- Chapter 3 also mentioned the **notion of CO_2 equivalent** which makes it possible to aggregate the effect on the climate of the various GHGs.
- Many industrial companies have established **carbon neutrality goals**[167] for 2050.

There are several methods for "measuring" the emissions associated with companies' portfolios of activities[168] but for the time being, they give different results. Standardization (as is the case for financial aggregates) would be necessary to have regular and comparable reporting.

For example, the Science Based Targets initiative[169] recommends a method for evaluating corporate carbon neutrality targets to verify whether they are consistent with the global temperature target of the Paris Agreement. It thus proposes, for several sectors, a basis for assessing companies' climate change strategies. As of April 2020, more than 350 companies have set targets using this SBT method and more than 500 have committed to do so in the near future.[170] In the energy sector, there is an SBTi methodology for electricity but not yet for the oil and gas sector.

ACCOMPANIMENT OF PUBLIC POLICY

The mobilization of public policies, informed by analysis or scientific recommendations, that will design plans accompanied by the means to achieve them is essential to achieve carbon neutrality. **Here are some examples:**

Laws

A European Union[171] regulation adopted in July 2021 sets the goal of legally obliging member states to reach carbon neutrality in the EU between now and 2050, with an intermediate goal, set for 2030 of -55 % net emissions (i.e. less the deductions for carbon sink absorptions) compared to 1990.

Many countries, particularly in Europe, have adopted energy transition laws.

In its Energy-Climate "*énergie-climat*" Act of 2019, France set its goal of achieving carbon neutrality by 2050, by dividing its GHG emissions by a factor of more than six between the years 1990 and 2050[172].

Germany approved the Energy Transition Act, which calls for the phasing out of electricity production from coal by 2038 at the latest, while these fossil fuels contributed 28% of the country's electricity production in 2019.

Building regulations

Numerous regulations exist in the building sector, which represents 40% of global GHG emissions according to the Global Alliance for Buildings and Construction.[173]

About 35% of the buildings in the EU are more than 50 years old and almost 75% of the building stock is energy inefficient. At the same time, only 0.4 to 1.2% (depending on the country) of the building stock is renovated each year. Renovation of existing buildings can lead to significant energy savings and plays

[167]Carbon neutrality within a given perimeter is a state of equilibrium to be reached between human-induced greenhouse gas emissions and their removal from the atmosphere by humans or by their actions. The difference between the gases emitted and extracted being equal to zero, carbon neutrality is also referred to as net zero emissions (NZE).
[168]The alignment cookbook: A Technical Review of Methodologies Assessing a Portfolio's Alignment with Low-Carbon Trajectories or Temperature Goal
[169]https://sciencebasedtargets.org/resources/legacy/2017/04/SBTi-manual.pdf
[170]https://sciencebasedtargets.org/
[171]https://ec.europa.eu/energy/topics/energy-strategy/clean-energy-all-europeans_en
[172]https://www.ecologie.gouv.fr/strategie-nationale-bas-carbone-snbc
[173]https://architecture2030.org/buildings_problem_why/

a key role in the transition to clean energy, as it could reduce the EU's total energy consumption by 5-6% and CO_2 emissions by about 5%.[174]

Renovating existing buildings is a real challenge. For example, the United Kingdom plans to renovate 27 million homes by 2050. This would require investments of around £1 trillion as well as a considerable mobilization, particularly in terms of manpower. To reach this goal in the next 30 years, it would mean renovating a city the size of Cambridge every six weeks.[175]

Transport regulations

Transportation accounts for about 17% of global GHG emissions (Figure 3.5). There is a great deal of regulation, particularly on fuel consumption and emissions from gasoline and diesel vehicles. In Europe, these regulations were considerably tightened when the countries of the European Union agreed in 2014[176] that carmakers should limit CO_2 emissions to 95 grams per kilometer across their model range by 2020. Emission regulations are set to get tougher as part of the EU's Sustainable and Intelligent Mobility Strategy published in December 2020.[177]

If the target is not met, car companies will have to pay fines of €95 per gram above the limit, multiplied by the number of cars they sell. By 2020, the total amount of fines is expected to be at least €500 million.[178] This regulation has driven European car manufacturers to bring more electric car models to the market.

Carbon Markets

Since 2005, Europe has created a market for CO_2 Emissions Trading Schemes, the EU ETS (Emissions Trading System).[179] Quotas are handed out to the industries that emit the most GHGs and that are considered to be a carbon leak risk. One quota is equivalent to the emission of one tonne of CO_2. Companies that have a surplus of quotas (because they have emitted less than expected) can sell them on this carbon market; conversely, companies that have a deficit of quotas can buy them. As in any market, the price of carbon is determined by these exchanges.

Since its creation, prices have varied greatly, reaching almost zero euros per tonne. Successive reforms, particularly the one implemented in 2019,[180] have stabilized this market and the price exceeded €50/t in May 2021. This is still a low price compared to the trajectory of the GHG emissions reduction needed to achieve carbon neutrality (at the price of $130/t$CO_2$ between now and 2030 according to the IRA's NZE scenario) and compared to what would be needed to make CO_2 capture and storage systems profitable. According to an estimate by the Global CCS Institute, the cost of CO_2 capture and storage ranges from £80 to £160/t (between 93 and 186 €/t).[181]

Since leaving the European Union, the United Kingdom has launched its own carbon market with a mechanism very similar to the

[174]www.capgemini.com WEMO 2020 17
[175]www.capgemini.com WEMO 2019 : Editorial Europe
[176]https://www.industryweek.com/the-economy/environment/article/22024227/carmakers-face-billions-in-european-co2-fines-from-2021#:~:text=If%20the%20
[177]https://ec.europa.eu/france/news/20201209/plan_mobilite_verte_durable_abordable_fr
[178]https://www.automobile-magazine.fr/toute-l-actualite/article/28823-objectifs-co2-des-amendes-a-payer-pour-volkswagen-ford-fiat-mercedes-et-volvo
[179]https://ec.europa.eu/clima/policies/ets_fr
[180]https://ec.europa.eu/clima/policies/ets/reform_fr
[181]https://publications.parliament.uk/pa/cm201719/cmselect/cmbeis/1094/109405.htm

European market. Prices reached £43.99 or €51/t in May 2021 when the market was launched.[182]

Europe is also concerned about what is called "carbon leakage". Indeed, European industries that pass on the cost of the quotas they must purchase in their prices lose competitiveness. This leads to European production being relocated to countries outside the European Union that do not have these constraints. This difficulty has led the European Union to envisage adopting a carbon tax at the borders to tax the carbon content of imported products. These imports would represent more than 20% of Europe's emissions. However, this project is also coming up against opposition from several countries exporting to Europe.

This example shows how difficult it is to set up rules that give a strong economic signal to encourage low-carbon projects if there is no corresponding international consensus. Nevertheless, this is an avenue to pursue.

Subsidies for the development of green energy

This was the case for a long time in Europe with the imposed feed-in tariffs. These tariffs were more expensive than market prices. This system, which is expensive for electricity consumers, was effective leverage accelerating the penetration of renewable energies. It is on its way out in Europe in particular. It is less necessary today, with the dramatic drop in the cost of renewable energy.

There are also many tax incentives, for example in France for the installation of photovoltaic panels

and biomethane units, and in the United States for new renewable electricity production facilities. At present, decarbonized hydrogen is also benefitting from subsidy schemes.

Public aids

As part of a 750 billion European recovery plan adopted in June 2020 following the Covid-19 pandemic, 30% of these funds will be dedicated to climate change topics. The German and French recovery plans will allocate 9 and 7 billion euros respectively to the development of green hydrogen. In the United States, Joe Biden has announced the attribution of 35 billion euros to develop clean energy technologies.[183]

Aid to developing countries

The developing countries are finding the energy transition to the decarbonized energies more difficult than the developed countries because of their need to face the fast-growing energy demand coming from the increasing population numbers and the higher living standards.

To dispense with the need for fossil fuels, especially coal (sometimes a national resource), it would entail making a considerable investment into new facilities, which is renderd difficult because of their limited available budgets. In addition, these countries often have no access to the necessary technologies or to trained personnel resources.

Article 9 of the Paris Agreement also stipulates that the developed countries are together committed to mobilizing $100 billion per annum to address the needs of the developing countries and assist them in the energy transition and alleviating the consequences of climate change. This financing is in the process of being set up.

Aid to the more vulnerable persons in developed countries

In addition, the energy transition for developed countries is liable to mean a higher cost to obtain energy, possibly obliging private parties to

[182]FT "UK carbon price trades at £50 as market opens for first time", 19 Mai 2021
[183]https://www.lemondedelenergie.com/biden-investissement-energie/2021/04/12/

invest and to more quickly replace some items of equipment that will no longer be authorized (for instance by buying an electric car although their ICE car is still in working order).

It is crucial to adjust these measures accurately and to accompany the consumers if we want to avoid causing issues of acceptability (as confirmed by the "*crise des gilets jaunes*" crisis in France in 2018-2019).

Aware of this difficulty, and with a concern for establishing a "fair transition", the European Commission has included in its highly ambitious decarbonation plan ("Fit for 55"), a "Social Climate Fund" of €72 billion, designed to support building renovations and has committed to subsidize private cars for vulnerable families and small companies.

PURSUING THE MOBILISATION OF COMPANIES

Many companies have set targets to reduce their GHG emissions. Among the 2000 biggest companies in the world ("Forbes Global 2000"), a large majority have made announcements in this sense. More than 20% of them have even set themselves the ambition to achieve "net zero emissions" (that is to reach carbon neutrality) over the next few decades.[184]

Within the framework of this mobilization, GHG emissions have been coded according to three perimeters[185]:

- Scope 1, which corresponds to direct GHG emissions generated by the company's activities.
- Scope 2, which corresponds to emissions associated with the consumption of electricity and heat.
- Scope 3, corresponds to indirect GHG emissions, such as those produced by the company's customers.

Global anthropogenic emissions are the sum of the scope 1 emissions of all the actors (including each one of us).

Carbon neutrality

To achieve **carbon neutrality,** companies that have set themselves this ambition are designing and implementing plans to:

1. **Avoid** emissions by implementing energy efficiency measures or by thinking about how we really use energy (international travel).
2. **Reduce** emissions by migrating toward higher-performing

[184]https://eciu.net/analysis/reports/2021/taking-stock-assessment-net-zero-targets
[185]https://www.bilans-ges.ademe.fr/fr/accueil/contenu/index/page/categorie/siGras/0

technologies or technologies that emit less (such as by using decarbonated electricity to power cars).

3. **Offset** : For the portion of remaining emissions that can't be reduced, they commit to:

- Finance equivalent emission reductions in other countries or sectors by purchasing "carbon certificates"
- Finance the capture of CO_2 in the atmosphere by purchasing carbon certificates corresponding to forest protection or extension.

Another example is RE100,[186] a global initiative that brings together the world's most influential companies that have committed to a 100% renewable electricity supply. In March 2021, there were 290 RE100 members, representing an annual electricity consumption volume of more than 278 TWh/year, equivalent to the consumption of Australia.[187]

Security of supply

For companies to ensure the **security of supply,** considerable investments will be necessary (in the order of thousands of billions of euros over the next ten years). The major energy companies, in particular, will have a significant role to play because of the substantial financial and human resources that will be required to invest in projects that are often very capital intensive and complex.

Green Investments

More and more companies are committing to green investments: solar photovoltaic, onshore and offshore wind power, battery storage, charging stations for electric vehicles and the manufacture of low-carbon hydrogen. These include major energy companies such as producers historically focused on oil and gas (TotalEnergies, BP, Shell in particular), electric utilities (EDF, Engie, ENEL, Iberdrola), but also today smaller companies supported by public or private funds. Some have converted, for instance the Danish oil company Dong, which is dedicated solely to offshore wind energy and has changed its name to Ørsted.

[186]https://www.there100.org/
[187]https://www.there100.org/media/2666/download

MAKING THE FINANCIAL SECTOR A MAJOR PLAYER IN CLIMATE RISK MITIGATION THROUGH REQUIREMENTS AS AN INVESTOR OR LENDER

Since 2015, many banks have pledged to stop financing coal-based investments. Financial institutions are also putting pressure on the management of the highest emitting companies. Thus in 2007, "Climate Action 100+" was created. This coalition brings together more than 500 international investors ($47,000 billion in assets under management) to put pressure ("shareholder dialogue") on the management of the world's 100 biggest emitting companies (to which 61 other companies were added in 2018). The United Nations is also supporting the Net-Zero Asset Owner Alliance of pension and infrastructure funds committed to decarbonizing their operations.

Public and private financial institutions are instituting environmental transparency rules for access to corporate financing.

In 2015, the Taskforce on Climate-Related Financial Disclosures[188] was created by international institutions to identify the information needed by investors to properly assess the risks and opportunities related to climate change. It develops recommendations on governance, strategy, risk management and related key indicators.

More generally, the extra-financial information requirements related to the climate and sustainable development stakes are increasing significantly for companies.

Financial instruments such as green bonds[189]

The companies issuing green bonds commit themselves, on the one hand, to the specific use to which the collected funds are raised, imposing that they will be used only for projects with a favorable impact on the environment, and, on the other hand, to the publication, each year, of a report to investors on the life of these projects.

The value of these bonds issued in 2021 will reach nearly $350 billion[190], a growth of nearly 57% in one year.

France is the country issuing the most green bonds in Europe with 25.8 billion euros of green bonds in the first half of 2020.

Export credit agencies

Some export credit agencies are tightening their conditions for project guarantees by linking them to climate objectives.

For example, the French government proposed in late 2020:

- The gradual tailing off of public guarantees granted for oil and gas projects
- The implementation of criteria restricting the granting of guarantees for thermal power plant projects
- And the introduction of a climate bonus mechanism for sustainable projects.

Similarly, in July 2020, in a move that marks a shift in its coal support policy, the Japanese government said it would tighten state-supported financing criteria for overseas coal-fired power plants.[191]

[188] Task Force on Climate related Financial Disclosures: https://www.fsb-tcfd.org/ https://assets.bbhub.io/company/sites/60/2020/10/FINAL-2017-TCFD-Report-11052018.pdf
[189] Also known as Green Bonds. https://www.latribune.fr/entreprises-finance/banques-finance/qu-est-ce-qu-un-green-bond-760714.html
[190] https://www.lemonde.fr/argent/article/2021/01/08/obligations-vertes-un-impact-ecologique-toujours-difficile-a-verifier_6065568_1657007.html
[191] https://www.reuters.com/article/us-coal-japan-finance/japan-tightens-rules-on-support-for-overseas-coal-fired-plants-idUSKBN24A0CH

ASSOCIATING CITIZENS AND CHANGING PEOPLE'S BEHAVIORS

The lifestyles of Western people are expected to become more energy and GHG emission efficient. Various studies show that there is no single factor that drives people to adopt energy-saving attitudes. Multiple factors such as financial or environmental concerns, competitiveness, cooperation, compliance, and altruism come into play. There are also barriers that prevent or limit behavior change (e.g., comfort, aesthetics, and physical design of homes).

An opportunity for transformation could arise from the change in work patterns related to the accelerating use of digital and remote communications and revealed by the Covid-19 pandemic. In June 2020, a global "energy-post.eu" study found that if all people able to work from home did so for just one day a week, it would save about 1% of global oil consumption for road passenger transport per year.

Taking into account the induced increase in household energy consumption, the overall impact on global CO_2 emissions would be an annual reduction of 24 million tonnes, equivalent to most of Greater London's annual CO_2 emissions. If everyone who could work from home did so for more than one day a week, the reduction in emissions would be proportionately greater.

[192]https://energypost.eu/calculating-the-energy-saved-if-home-working-becomes-the-norm-globally/

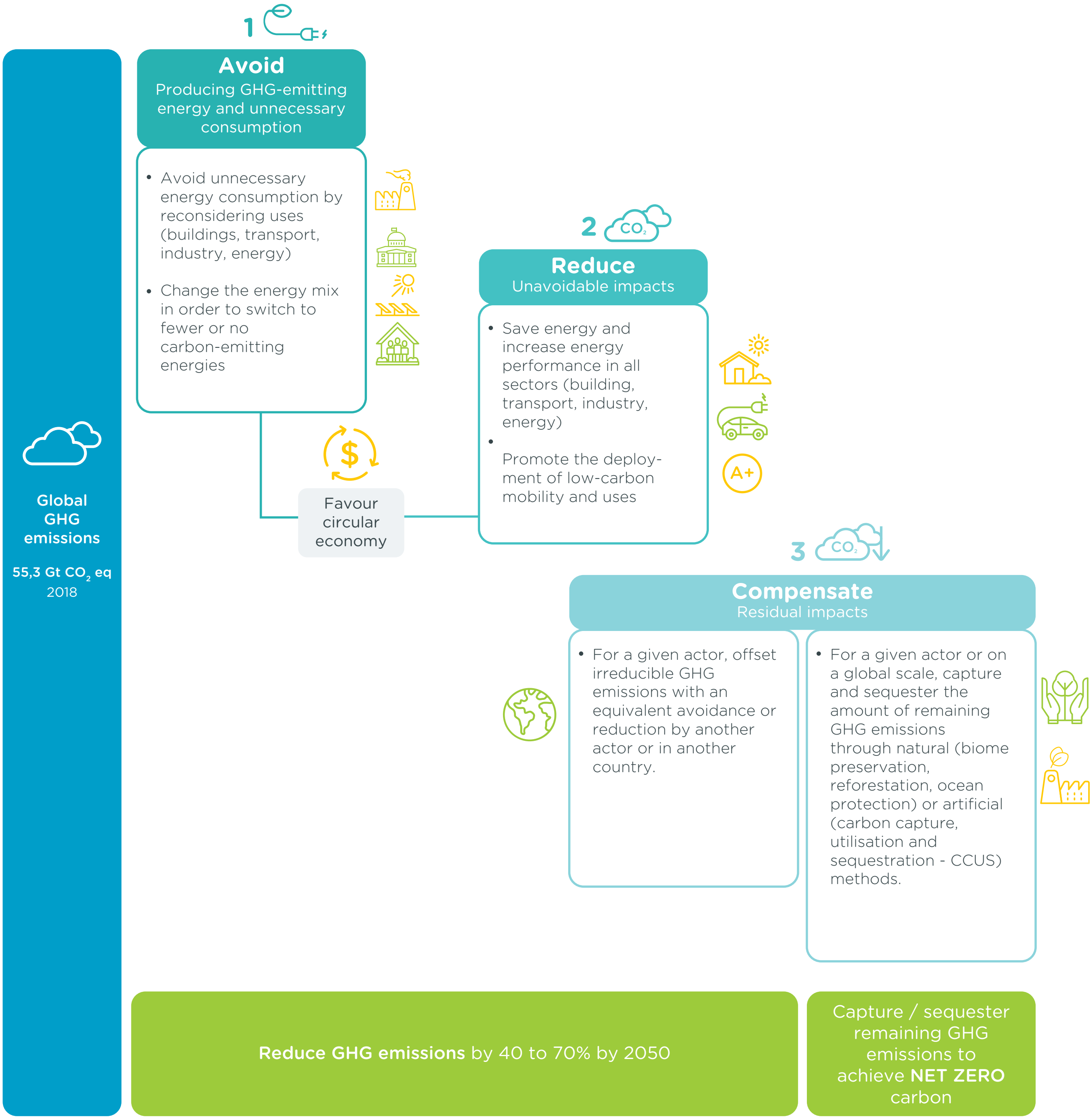


Figure 5.3: Levers to reduce GHG emissions and achieve Net Zero
Source: Capgemini analysis & UN Environment – Emissions Gap Reports 2019 & IPCC, 2014: Climate Change 2014: Synthesis Report

Note: Emissions scenarios leading to CO_2-equivalent concentrations in 2100 of about 450 ppm or lower are likely to maintain warming below 2°C over the 21st century relative to pre-industrial levels. These scenarios are characterized by 40 to 70% global anthropogenic GHG emissions reductions by 2050 compared to 2010, and emissions levels near zero or below in 2100.

5.2 Conclusion

This document is aimed at providing an understanding of the short- and long-term dynamics of energy production and consumption as well as GHG emissions.

The challenge of ensuring the security of energy supply necessary for the well-being of people while preserving our planet is considerable.

When looking at the facts, it becomes clear that:

- An available, reliable, and clean energy supply at affordable prices is essential to the well-being of the people
- There is no "ideal energy" and that it is therefore necessary to think in terms of energy and electricity mixes
- Scientific and technical progress as well as societal changes lead to changes in uses and in the energy sources best suited to meet them,
- Consumers are increasingly concerned about climate change,
- Improving energy efficiency, mainly in developing countries as well as in developed countries, is a challenge that must be met
- GHG emissions continue to grow[193] in ways that are inconsistent with the objectives of the Paris Agreement, and that it is urgent to deploy all means to reduce them to move onto a trajectory that minimizes the temperature increase of our planet,
- We all have a role to play as states, local authorities, cities, companies, and citizens.

With this in mind, this document endeavors to give readers the keys needed to understand these complex topics.

[193]Except in 2020 for reasons due to the pandemic

DISCLAIMER:

This document is for information purposes. The authors sought to provide a synthetic account of the main energy issues, but do not purport to be exhaustive of existing sources on energy and scientific data on climate change.

The English version of this document is a translation of the original version in French, available at the same website.

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