1

Different Forms of Energy

1.1. Energy at the heart of the development of civilization

The term “energy” is taken from the Greek *energon*, which means “force in action”. Energy is the capacity to perform work, impart movement or raise temperature (heat a building, cook food, etc.). It is produced via the use of natural forces like wind or solar energy, from the combustion of fuels or combustible materials (oil, gasoline, diesel fuel, fuel oil, natural gas, coal, wood, etc.) or from electricity.

Energy has always been vital for humankind. Living organisms use a large quantity of energy, for which the main natural source is the sun. Human beings obtain their energy from food, which is transformed in the cells of their bodies during a multitude of biochemical reactions allowing them to maintain their body temperature, grow, multiply and move about.

Although the rest of the animal kingdom has always been content with what nature provides for it, humankind has been able to free itself from the weather variations and random food resources that threatened the demographic growth of its species. Through the discovery of fire, humans were able to cook food – leading to the development of agriculture and breeding – and produce heat, thereby promoting their longevity. In addition, this allowed them to forge tools and weapons to ensure their survival.

Much later, various energy innovations helped to shape society as we know it today. Energy is present at every moment of our lives. These innovations such as motors operate with petroleum products, gas or electricity.

In the same fashion, light has become indispensable to us. Light that once came from a candle, then from oil lamps and street lamps powered by town gas, today is mainly produced by electricity.

Therefore, energy, now essential to our well-being (reduction of physical effort, heating and lighting of premises, etc.) and economic development, has become a key element of progress.

However, energy needs continue to increase, although today nearly 2 billion people still do not benefit from even the simplest of modern energy resources.

Access to abundant and inexpensive energy sources and an increasing worldwide population are leading to an explosion in the demand for energy at the same time as humankind is becoming aware of the impact of its lifestyle on the environment. The survival of the human species now depends on its intelligence and creativity.

1.2. Energy: major stages and innovations in its history

In antiquity, the only resources available were manpower (it is estimated that one-third of the population of Rome was composed of slaves), animal traction (for transport) and biomass, in particular wood for cooking and heating. In Europe during the Middle Ages, the use of windmills was imported from the Orient, providing efficient energy, particularly for the industries of food (nuts and olives) and textiles (fabric milling). More powerful watermills allowed for the development of paper mills and iron mills.

Modern forms of energy did not make their appearance until just over 200 years ago, starting with coal. In the 18th century, England had exhausted its forestry resources and started to use its coal resources to develop the use of the steam engine, thereby paving the way for the advent of the industrial age.

The next step was the discovery of electricity. The principle was known quite early on, but it was only at the end of the 19th century that electricity really became a source of energy.

Another step was the “discovery” of oil. In fact, it was used (because its existence had been known for a long time) from 1860 onwards to make paraffin, which was used in oil lamps, then for motor transport with the invention of the petrol engine and the diesel engine at the end of the 19th century and finally as fuel for ships, particularly warships, around 1910.

In the 20th century, electricity consumption grew first from coal-fired plants, then from heavy fuel oil, later from nuclear reactors and combined cycle gas turbines and at last from renewables.

Finally, the 21st century will undoubtedly see a shift in the share of different energy sources in total production (the energy mix) to reduce CO_2 emissions and limit climate change, with a reduction in the consumption of fossil fuels and an increase in the share of hydroelectricity, wind power, solar energy, geothermal energy, biomass, etc.

1.3. Energy demand

After World War II and throughout the second half of the 20th century and the beginning of this century, global consumption of primary commercial energy exploded, rising from 2 Gtoe (gigatons or billions of tons of oil equivalent) in 1945 to around 15 Gtoe or 600 exajoules in 2023. This increase is the result of strong economic growth after World War II until 1973 and again after 2000, combined with the discovery of major oil, natural gas and coal deposits, particularly at the end of the 20th century.

Commercial energy is energy that can be bought or sold. It includes oil, natural gas, coal, electricity from nuclear and hydro sources and new renewable energies.

Non-commercial energy corresponds to traditional biomass (wood and charcoal) which, particularly in developing countries, is directly harvested and used by the consumer.

Box 1.1. *Commercial and non-commercial energy*

To illustrate commercial energy consumption in 2023, imagine a cube measuring 2.4 kilometers on each side (about three times the height of the Burj Khalifa tower in Dubai) filled with oil: this is equivalent to the total amount of energy consumed in the world each year.

Oil as such accounts for only 32% of this quantity, i.e. consumption of 150 m^3 per second, equivalent to the flow of the Seine in Paris. The rest is consumed in the form of natural gas (24%), coal (26%), nuclear power (4%), hydroelectric power (6%) and new renewable energies (8%) (Figure 1.1).

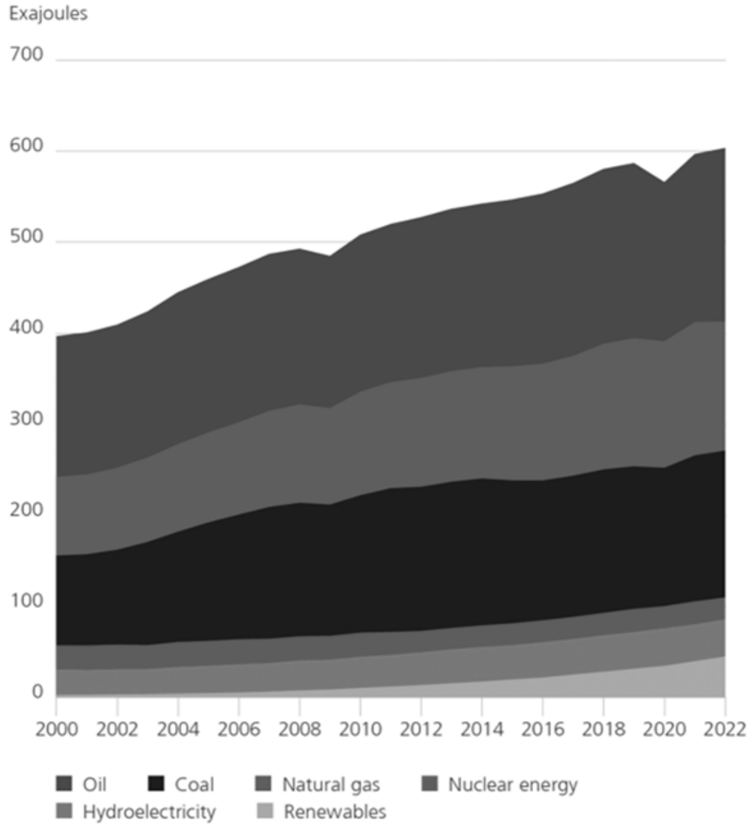

Figure 1.1. *World energy consumption by energy source (source: EI Statistical Review of World Energy 2023). For a color version of this figure, see www.iste.co.uk/favennec/geopolitics1.zip*

In addition to the consumption of so-called "commercial" energy, we need to add the consumption of non-commercial energy. This is mainly biomass (especially firewood for cooking, particularly in Africa, where access to "modern" energy is difficult), which represents between 1.5 and 2 Gtoe.

The world can be divided into several groups, each using one of the three energy systems that have succeeded one another throughout history: wood and human or animal power in much of sub-Saharan Africa and the Amazon; coal in China and India; and oil in the Organization for Economic Cooperation and Development

(OECD) and producer countries. The development of renewable energies is gradually changing this situation.

After a period of moderate growth in the 1990s, energy consumption grew much more rapidly between 2000 and 2010. Global economic expansion, extremely strong growth in China and, to a lesser extent, India, and sustained demand in the United States (until 2008) all contributed to this increase. For many years, China commissioned a new coal-fired power plant every week, and each plant had a capacity of around 1 GW (equivalent to a conventional nuclear power plant). China's total electricity generation was 8,850 Twh in 2022, up from 3,287 Twh in 2007, an annual increase equivalent to the UK's annual electricity consumption.

Global energy consumption continues to rise, but at a slower rate (1.5–2% per year) since 2010, significantly slower than global GDP, which is increasing by 3% per year. Oil consumption is growing by around 1.5% a year, gas by 3%, while coal consumption remains stable. Hydroelectricity consumption is growing at a slow pace, while consumption of new renewable energies (wind, solar, etc.) is increasing by more than 10% a year, although they still account for only a small proportion of the energy mix.

1.4. 2020: Covid-19's impact on energy demand

In 2020, global energy consumption and production fell by around 5% as a result of the Covid-19 pandemic, which paralyzed the world economy. Oil consumption fell by 9% compared with 2019, while gas consumption fell by 2% and coal by 4%. Oil prices collapsed to historically low levels at the start of the year.

Conversely, renewable energy production continued to grow at a rate of 10%, slightly slower than in previous years. The Covid-19 crisis highlighted the resilience of renewable energy production. The pandemic may have provided a glimpse of a cleaner, low-carbon world thanks to the reduction in CO_2 emissions and air pollution. However, by 2022, energy consumption had exceeded its 2019 level and pollutant emissions were back on the rise.

1.5. Drivers of energy demand: wealth

Wealth is the determining factor in energy consumption. On average, each citizen of the United States has an annual income of around 66,000 dollars (GDP per capita 2022). This income is 40 times higher than that of a West African citizen (around 1,000–2,000 dollars a year). The annual energy consumption of an American (just over 7 tons of oil equivalent) is also around 20–30 times higher than that of an African citizen (consumption can vary from 100 to 700 kg of oil equivalent, excluding biomass, depending on the country, Figure 1.2).

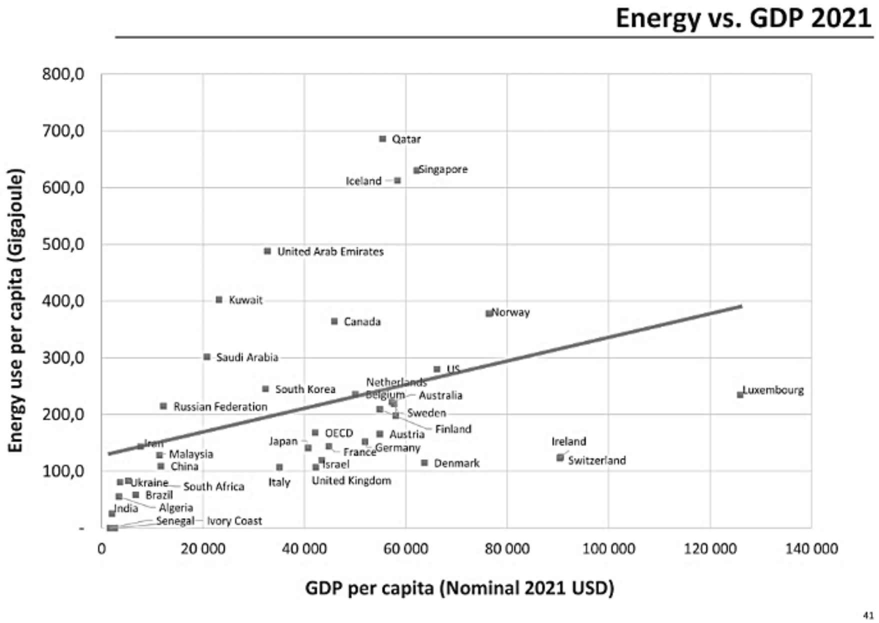

Figure 1.2. *Commercial energy consumption and income (source: World Bank and BP Statistical Review 2022)*

Energy consumption rises very rapidly with income, particularly when income is low and countries are in the process of industrialization. Then, when services play a more important role in the economy, energy consumption rises more slowly than income. In developed countries, for example, the ratio between growth in electricity demand and economic growth is around 0.6, while in developing countries, the ratio is over 1.

At higher income levels, energy consumption rises very slowly, as household appliance use nears saturation.

Therefore, the number of automobiles stabilizes, and the number of heating appliances and household appliances per household no longer increases in the wealthiest countries. Energy consumption is simply keeping pace with demographic growth (Figure 1.3).

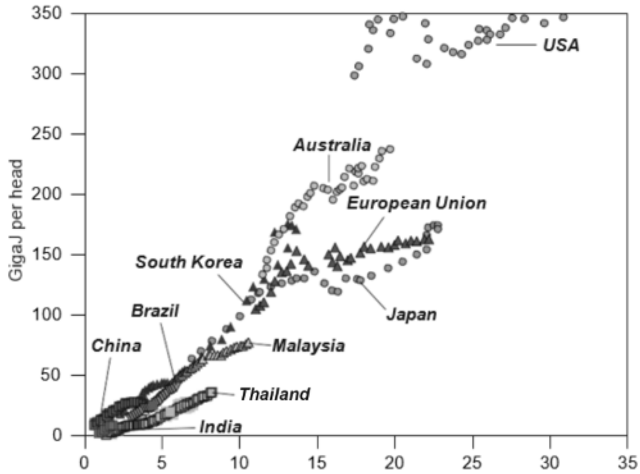

Figure 1.3. *Evolution of energy consumption (in gigajoules per capita) as a function of wealth (GDP in thousand dollars per capita). For a color version of this figure, see www.iste.co.uk/favennec/geopolitics1.zip*

If we analyze the relationship between energy consumption and wealth, we can identify several groups of countries:

– First, there are the major non-OECD oil-producing countries (the Middle East and Russia), whose energy consumption is very high in relation to their income. They consume a lot because energy is made available to consumers at a low price, since energy is abundant.

– Second, the energy-rich OECD countries (USA, Canada, Norway, Australia), whose per capita income is much higher than that of the previous group and whose per capita consumption is relatively high. Their consumption has risen partly because their oil, gas, coal and hydroelectricity resources are abundant, and there is no need for them to seek to optimize their energy consumption.

– The third group includes the major European countries and Japan, most of which have no energy reserves and which, despite high per capita incomes, limit their energy consumption in order to reduce imports.

– Finally, as already mentioned, there are the world's poorest countries, where per capita commercial energy consumption (excluding wood) is low, both as a consequence and a cause of still-limited economic development.

Other factors influence a country's energy consumption:

– Climate has a direct effect on the use of lighting, heating and air-conditioning.

– Geography influences the transmission network.

– Industrial facilities such as mining, shipbuilding, chemicals, glass and metallurgy consume large quantities of energy.

– Cultural factors influence energy consumption, as shown by the differences in consumption between Northern Europe and the United States or Australia.

1.6. Different forms of energy

1.6.1. *Main forms of energy*

The main forms of energy are as follows:

– Mechanical: the cause or result of a change in potential energy (e.g. waterfall) or kinetic energy (movement).

– Thermal: expressed in the form of heat.

– Chemical: liberated via a chemical reaction that can be explosive.

– Electrical: produced by a difference in electrical charge between two points; can result in a direct electrical current.

– Nuclear: can be created by fission (splitting atomic nuclei) according to the principle of nuclear reactors currently in use or by the fusion of atomic nuclei (two nuclei combine to form a new, single nucleus with the release of energy). Nuclear fission has been widely used since World War II. First, there was the development of the atomic bomb and then the start of the use of nuclear energy for electricity generation in the United States in the 1950s. However, electricity generation by nuclear fusion is still in the research phase.

Over 30 countries produce nuclear electricity. However, various accidents (Chernobyl, Fukushima) have limited or halted the development of nuclear power in many countries.

1.6.2. *Fossil fuels and renewable energies*

1.6.2.1. *Fossil fuels*

Oil, gas and coal still account for over 80% of energy consumption. A detailed description of these energies is given below. Nuclear energy can be considered a fossil fuel, since the uranium needed to produce it is a fossil resource.

1.6.2.2. *Renewable energies*

In the International System (SI), the unit of energy is the joule, which represents the work done by a force of one Newton (N) traveling a distance of one meter. Another definition comes from energy's use to heat water. Therefore, a calorie is the quantity of energy required to raise the temperature of one gram of water by one degree Celsius. Physicists have shown that this energy, referred to as calorific or thermal, is equivalent to mechanical energy (or work). Another important type of energy is electrical energy: the joule is also the energy produced by a direct current of one ampere at a voltage of one volt for one second.

Another important concept is power, which is measured in watts (W), and is the energy consumed or generated per unit of time, i.e. one second: 1 watt is equivalent to 1 joule/second. For large facilities, power is expressed in kilowatts (1 kW = 1,000 W) or megawatts (1 MW = 1,000 kW) and energy in kWh, i.e. 1 kW (produced by a generator or consumed by a machine) for one hour.

Oil companies use the metric ton of oil equivalent (toe), which is the energy that can be produced by one metric ton of oil, or the barrel of oil equivalent (boe), which is the energy that can be produced by one barrel of oil. Gas can be measured in cubic feet or cubic meters and its calorific value in kWh or British Thermal Units (BTUs).

International statistics are now increasingly provided in joules or exajoules.

One fundamental property of energy is that it can be converted from one form to another, with the following equivalents:

1 calorie = 4.18 J.

1 toe = 42 billion J (approximately).

1 toe = 42 million BTU (approximatively).

1 kWh = 36 million J.

Box 1.2. *Units*

Renewable energies include the following:

– Biomass: a versatile source of energy which can provide heat and electricity. It includes wood, which is used as a cooking fuel. It consists also of gas and liquid fuels produced from all organic matter derived from living organisms.

– Hydraulic: produced by the movement of water.

– Wind: which powers windmills.

– Solar: produced by solar radiation. There are several forms of solar energy:

- solar thermal energy used to produce hot water in a dwelling;

- concentrated solar power which uses a parabolic system to concentrate solar rays onto a heat transfer fluid, often water or melted salt, in a pipe or another vessel, thereby generating steam and ultimately producing electricity;

- solar photovoltaic energy which directly transforms some of the sun's rays into electricity via panels made up of cells;

- tidal energy.

– Marine energy: produced from marine currents or from swells and waves.

– Geothermal: heat generated in the Earth's core.

Fossil energy resources (coal, oil, natural gas, uranium) are by definition limited. The time needed to replenish them is on a planetary scale (tens of millions of years) not a human one. Conversely, renewable energies are permanently created by nature, but the resources available depend on natural conditions:

– solar energy (day/night);

– wind energy (strong wind/dead calm);

– hydraulic energy (large river/absence of precipitation).

Prefixes	Symbols	Values	Examples
Kilo	K	10^3 (thousand)	Kilowatt (kW)
Mega	M	10^6 (million)	Megawatt (MW)
Giga	G	10^9 (billion)	Gigawatt (GW)
Tera	T	10^{12} (trillion)	Terawatt (TW)
Exa	E	10^{18}	Exajoules (EJ)

Table 1.1. *Commonly used multiples*

1.7. The laws of energy

Different forms of energy change continuously from one to another: light energy to thermal energy, chemical energy (from fuels or food) to mechanical energy, nuclear energy to heat, mechanical energy to electrical energy, etc. Yet these conversions are subject to two principles of thermodynamics:

– The principle of the conservation of energy: the quantity of energy subjected to a transformation process is equal to the energy output in other forms once the process is finished.

– The principle of degradation of energy: in a closed system, the quantity of energy that is available for use must diminish. Therefore, an electric motor transforms electrical energy into mechanical energy and operates by releasing heat (the motor heats up). This heat generally goes unused.

Nonetheless, there are limits to the energy conversions possible: a car's brakes slow it by transforming kinetic energy into heat, but we cannot move a car forward by heating the brakes.

Different energy sources may be used for the same purpose. For example, heat can be produced by burning wood, coal, gas or petroleum products or by using nuclear energy. In the same way, electricity can be generated from many forms of primary energy (e.g. natural gas, oil or coal in a thermal power plant). For the time being, transport still relies heavily on oil-based products: petrol, diesel, heavy fuel oil (for ships) and jet fuel. Of course, electric vehicles are becoming increasingly important.

There is a further distinction between three types of energy sources:

– energy sources such as fossil fuels which can be stored;

– flux energies, which are characterized by random availability and cannot be stored (wind and solar energy);

– semi-renewable energies such as biomass (depends on replacement planting) or hydroelectricity (depends on precipitation).

Primary energy is energy directly resulting from the exploitation of a resource available in nature: wood, coal, oil, natural gas, wind, solar radiation, hydraulic or geothermal energy. However, these energies cannot always be used directly, they must first be converted (e.g. oil refining to obtain gasoline).

Secondary energy results from the transformation of a primary energy by the use of a conversion system: for example, electricity (secondary energy) is produced via the use of coal (primary energy) or gas (primary energy) in a thermal power plant or uranium (primary energy) in a nuclear power plant. It can also be produced by water, wind or sun.

Changing primary energy into secondary energy involves transformation or conversion losses.

Box 1.3. *Primary and secondary energy*

In order to analyze global energy consumption, we must add up – and therefore compare – the consumption of oil, coal, gas, etc. A common unit is used for these comparisons: the joule is increasingly used, but the ton of coal equivalent and then the metric ton of oil equivalent (toe) have long been the main units of measurement. The ton of oil equivalent – which we will use extensively in this book – is the quantity of energy contained in one ton of crude oil.

Why do we refer particularly to the "oil equivalent"? Simply because oil is the most widely used energy source. Fifty years ago, the ton of coal equivalent was used. To generate the same quantity of heat as that contained in one ton of oil, we must burn roughly 1.5 metric tons of high-quality coal (anthracite); for lignite (a low quality form of coal), a larger quantity is required. Likewise, 1,100 cubic meters of "gaseous" natural gas are needed to obtain the energy contained in one ton of oil equivalent. The energy content of liquefied natural gas (LNG) is greater than that of oil: one ton of LNG is equivalent to 1.23 toe.

The case of electricity, which is a secondary energy, is more complex.

The quantity of heat provided by 1 kWh is equivalent to that provided by 0.083 kg of oil. Therefore, 1,000 kWh = 0.083 toe.

However, the average efficiency of a power plant is of the order of 38%. Therefore, approximately 0.083/0.38, i.e. 0.22 kg of oil equivalent, is needed to generate 1 kWh. Using this input assumption, 1,000 kWh = 0.22 toe. This is the equivalence that is generally used to convert kWh into toe, particularly for nuclear energy.

Quantities	Calorific equivalents
1,000 m^3 of natural gas	0.9 toe
1 metric ton of LNG	1.23 toe
1 metric ton of coal (anthracite)	0.67 toe
1 metric ton of coal (lignite)	0.33 toe
1 megawatt-hour (MWh)	0.22 toe (production) or 0.083 toe (consumption)

Table 1.2. *Calorific equivalents*

It should be remembered that primary energy (coal, oil, gas, renewables) is directly burned or transformed into secondary energy for use.

"Final energy" is the energy that is delivered to consumers (in the form of electricity, gasoline, etc.) and then transformed by them into useful energy (lighting, heating, transport, etc.). At every stage of the process, however, losses are incurred. Between the secondary energy (after transformation of primary energy) and the final energy (received by the consumer) losses resulting from transformation are incurred.

Useful energy is the energy available to the consumer after losses in the equipment which is used. For instance, in a car, only a fraction of the energy contained in the gasoline or the diesel is effectively used to drive the car.

Considering all energies together, energy losses between primary energy and useful energy can be broken down as follows:

– 25% during conversion;

– 5% during transport;

– 35% during end-use.

The result is that useful energy only represents one-third of the primary energy used in the process.

Box 1.4. *From primary energy to useful energy*

1.8. Electricity

Worldwide electricity production reached some 29,165 TWh in 2022. Had this electricity been entirely of thermal origin, it would have required the use of 6 billion tons of oil equivalent, equivalent to one and a half times total world oil production for that year. Electricity use is growing more quickly than that of any other form of energy: its production was less than 1,000 TWh in 1950.

However, several hundred million people on the planet still do not have access to it, and one of the major challenges in the years to come will be to reduce this number. Those without electricity are mainly concentrated in Africa.

Projects to increase electricity supplies have been met with variable rates of success. China and India's achievements in this domain have been spectacular: 100% of Chinese households and 95% of Indian households now have electricity, although only 30 years ago the proportion was very low.

– Voltage (V): analogous to pressure.

– Current (I): analogous to flow – measured in amperes.

– Power (P) = V × I measured in watts. A watt is 1 joule per second.

– Impedance (Z) = V/I measured in Ohms.

– Electrical energy = power x time, is measured in watt hours (Wh) or multiples of that such as kilowatt hours (kWh, 10^3 Wh), megawatt hours (MWh = 10^6 Wh), gigawatt hours (GWh = 10^9 Wh), terawatt hours (TWh = 10^{12} Wh), etc.

Frequency of alternating current is measured in hertz.

Box 1.5. *Units for electricity*

Electricity has several particular characteristics:

– It is very difficult and costly to store. Of course, dams can be considered as stores of electricity. Traditional dams are good storages of energy. Another system can be used: pumped-storage energy transfer stations where surplus electricity produced during off-peak hours (times of low demand) can be used in mountainous regions to pump water from one dam to another at a higher location. This water can be released during times of high electricity demand and can help to smooth out differences between supply and demand. Batteries are valuable, but they are costly and do not allow very large storage. Production must therefore be in real time; it must continuously adapt to demand.

It is the consumer who controls demand, and this demand fluctuates continuously. Electricity is supplied from the producer to the consumer instantaneously, and so users never have to wait for their supplies.

Electricity can travel through all links in the network, so according to the law of physics, it is difficult for the producer to determine the supply route the energy will take.

A distinction must be made between production during off-peak hours and production during peak hours. The former is base-load production. Base-load generating plants operate continuously to meet that portion of electricity demand that is constant, i.e. the level below which demand does not fall. In contrast, plants used for peak-load generation are only used as needed to respond to peaks in consumption, the timing of which is not always predictable. However, it is essential that production capacity is adequate for peak demand.

These physical characteristics result in the following specific characteristics of the electricity market:

– Limited storage is possible, making it continuously necessary to balance supply and demand.

– No substitution is possible over the short term.

– Demand is highly dependent on time and very sensitive to temperature variations.

– Significant losses occur during distribution (e.g. average losses in Europe are in the order of 5% throughout the high-voltage network). The location of generating plants is therefore determined by two considerations. The first is the advantage of proximity to areas of consumption. The second is the benefit of optimizing the site's position with regard to the fuel supply (coal-fired power plants close to coal mines or ports) or in consideration of technical and environmental constraints (nuclear power plants close to a source of cold water such as rivers or oceans).

– However, despite the above, it is possible to transport electricity over large distances For instance, the distance is 1,200 km (720 miles) between Canadian hydroelectric power plants and major centers of consumption. Transportation is made via very-high-voltage lines (735 kilovolts). Therefore, it is possible to trade electricity between neighboring countries when production costs are far lower in a given country. Thus, Canada and Norway are very large producers of hydraulic energy, and this energy is exported (in the case of Canada, to the USA; in the case of Norway, to countries of Northern Europe through interconnected lines).

1.8.1. *Electricity generation*

The sources of electricity supply vary considerably (Figure 1.4):

– Thermal processes operate by producing steam from water or hot gases by combustion and passing them into a turbine to make it rotate. This rotation drives an alternator that generates electricity. The steam is produced by the combustion of wood, coal, gas, oil or petroleum products (diesel, heavy fuel oil or even crude oil), or by splitting atoms, or even by concentrating sunrays on a heat transfer fluid.

– Electricity can also be generated hydraulically by water flowing through turbines or by wind-driven turbines.

– Electricity can be produced by photovoltaic cells that transform solar radiation into electricity without the use of turbines.

– Electricity can also be generated using geothermal energy, ocean energy, etc.

Most electricity produced throughout the world comes from fossil fuels. The main source remains coal (38% of electricity is produced from coal, and roughly 75% of coal is used to produce electricity), particularly in major coal-producing countries like the USA, China, India, South Africa and even Germany. The use of oil is decreasing because of competition from both coal, which is cheaper, and natural gas, which is not only cheaper but also less polluting.

Natural gas is being used more frequently, thanks to the efficiency of combined cycle gas turbine (CCGT) power plants. Here, electricity is generated first by expanding the gas burnt in a turbine, then by expanding the steam recovered by using the heat from the burnt gas in a second turbine. This process is favored by the low cost of power plant construction and the significant reduction in pollutant emissions (no dust or sulfur oxides, and lower CO_2 emissions than coal or oil). However, the use of gas plants very much depends on the price of gas.

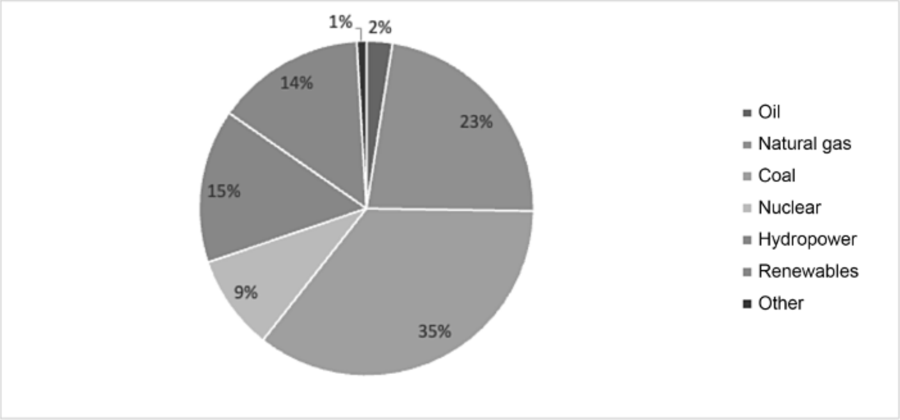

Figure 1.4. *World electricity generation by origin (source: IE Statistical Review of World Energy 2023). For a color version of this figure, see www.iste.co.uk/favennec/geopolitics1.zip*

Nuclear energy went through a strong development phase in the USA during the 1950s, then in France, Japan and several European countries during the oil shocks of the 1970s. However, its development was halted by incidents such as that of Three Mile Island in the USA in 1979 and particularly by the accident at Chernobyl in 1986, and finally by the Fukushima accident in March 2011. In many countries, large proportions of the population are opposed to nuclear energy because of the risk of accidents and fears associated with nuclear waste storage, and this opposition has been strengthened by the damage at Fukushima in March 2011 (a tsunami submerged the cooling systems of several power plants, resulting in several explosions that neutralized part of the Japanese territory). For several years now, nuclear power generation has been more or less stable worldwide.

The development of hydraulic energy, which was significant in Latin America and Europe following the war, seems to have reached a saturation level with the construction of the Three Gorges Dam in China. That was inaugurated in May 2006 and has a capacity of roughly 22 GW, 20 times that of the typical nuclear plants built in the 1980s. Other very large dams already exist (Chapter 2) or will be built in the future.

Electricity is generally produced in large plants to permit production at a low average cost to benefit from the economy of scale. Some countries (Figure 1.5) still rely on diesel power plants operating with heavy fuel oil or even diesel fuel. Production costs are extremely high, due to the high price of fuel oil and even more so of diesel. Nigeria is an interesting case in point: the country has 13 GW of power generation capacity, but only 5.5 GW is available (for a population of over 200 million; in France, the capacity is 120 GW for 67 million inhabitants). Also, despite the widespread availability of gas, these power plants are not always operational, for both political and technical reasons. Access to electricity for the population connected to the grid does not exceed a few hours a day. There is therefore a huge market for small diesel-powered generators.

The share of renewables in electricity generation is increasing very fast, reaching 14% in 2022. In addition, renewables accounted for over 40% of global primary energy growth in the last years. This increase is mainly due to Europe, Brazil, the United States and China.

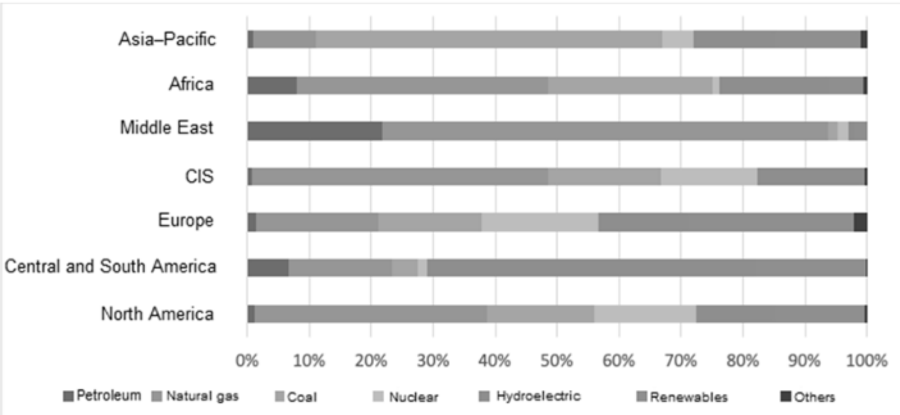

Figure 1.5. *Electricity generation by source, by region (in %) (source: EI Statistical Review of World Energy 2023). For a color version of this figure, see www.iste.co.uk/favennec/geopolitics1.zip*

Electronuclear energy is based on the use of uranium as a fuel to produce electricity. Uranium is a highly concentrated source of energy and is available throughout the world in what are considered to be sufficient quantities. In most reactors operating today, one ton of uranium can produce roughly as much electricity as 15,000–20,000 tons of coal. Today, there are some 440 nuclear reactors in operation in 30 countries, with a combined capacity of 400 GW. In addition, 56 new reactors are under construction in 15 countries, including China, India and Russia.

When an additional neutron is added to the nucleus of a uranium atom, it splits and releases thermal energy. When the nucleus splits, several neutrons are released, which will in turn collide with other nuclei and result in new fission reactions in other uranium atoms. This leads to a chain reaction. The heat produced during fission transforms a heat transfer fluid (often water) into steam, which then powers a turbine and produces electricity.

There are various types of nuclear power plants based on different types of heat transfer fluids and coolants (the term "moderator" is preferred for the element that slows – or cools – the neutrons): graphite-gas, ordinary water (light water reactors (LWRs)), heavy water, boiling water, fast neutrons (breeder reactors), etc. Ordinary water (or LWR) nuclear plants are most widely used throughout the world, particularly those which use pressurized water (abbreviated to PWR: pressurized water reactors, which represent 60% of worldwide nuclear power plants).

During the primary combustion of uranium, plutonium is released as a byproduct. This plutonium can be partially reprocessed and then used as a new fuel source. Pure plutonium is only used in fast reactors, often for research purposes (Japan, the United States and Phoenix in France), but the Superphoenix reactor was intended for the commercial production of energy. Most of the time, the plutonium is mixed with uranium: the fuel produced in this manner is called MOX (mixed oxide) and can be used either in adapted LWRs or in fast neutron reactors. In France, 20 of the 58 PWRs are equipped to operate with this type of fuel. Its use is also authorized in Japan, Germany, Belgium and Switzerland.

Currently, the first generation III reactors are being built, such as the European Pressurized Reactor (EPR). These reactors have higher capacity and a longer operating life. However, research is now underway into generation IV reactors, which will have far higher efficiencies and so be able to produce up to 50 times more electricity from uranium than today's plants. An international collective known as the *Generation IV International Forum* was created by the United States in 2000. It represents 13 countries committed to jointly developing this new generation of nuclear reactors by sharing research and development.

Box 1.6. *Nuclear electricity today*

The advantage of nuclear energy is that it does not produce greenhouse gases. However, it does give rise to radioactive waste and the storage and disposal of this must be managed with care to minimize the risk to people and to the environment. Although its radioactivity decreases over time, the handling of this waste remains a very important concern over the long term as radiation can continue for many decades.

1.8.2. *The atom: will it lead to the third energy revolution?*

Known uranium resources, accessible at a cost of less than 130 $/kg, are sufficient for existing nuclear power plants to operate for at least 100 years. The cost of natural uranium represents only a small percentage of this nuclear electricity cost. Uranium deposits, which are relatively abundant, have been little explored to date. Uranium reserves could therefore be considerable.

Prior to the Fukushima accident in March 2011, despite the waste problem, there was talk of a nuclear renaissance. From North America to the Middle East and Southeast Asia, the vast majority of nations seemed ready to revive nuclear power.

Figure 1.6. *Nuclear power plant*

After the Fukushima accident, which led to the shutdown of almost all nuclear power plants in Japan, the situation changed. The challenges that the nuclear industry now faces are considerable: public reluctance to accept the risks of accidents and the problem of waste disposal, the complexity of the political processes involved in setting up or developing the industry, the small number of players with the necessary construction know-how and extremely high barriers to entry. The development of nuclear power is therefore uncertain.

Nuclear power capacity is growing rapidly in Asia, where there are currently 130 nuclear reactors in operation, 35 under construction and plans to build 70 to 80 more. China is set to see the biggest increase in nuclear power generation. Between 2007 and 2023, it increased its nuclear power generation by 500%, with a capacity of 54 GW (51 reactors) and an output of around 420 Twh in 2022. A total of 24 reactors are currently under construction, and the aim is to reach a capacity of 400 GW by 2060. India is also committed to increasing its nuclear power generation capacity to 22.5 GW by 2031 (from around 8 GW at present). India has developed power plants using thorium as fuel (instead of uranium) and has several advanced facilities for this purpose.

Studies are underway to try to reproduce the atomic fusion reactions that take place within the sun's core. Proposed in the mid-1990s, the International Thermonuclear Experimental Reactor (ITER) project was launched in 2010 with the experimental reactor built in France, at the Cadarache site. The ITER project is a collaboration of 35 nations around the world. The seven core members – China, the EU, India, Japan, South Korea, Russia and the USA – signed the ITER Agreement in 2006, agreeing to share the costs of construction, operation and decommissioning of the project. The sums involved are more than 10 billion dollars.

The production of helium from the fusion of heavy isotopes of hydrogen (deuterium and tritium) has still only been achieved on an experimental scale because the conditions for fusion are extremely difficult to produce. A temperature of 100 million degrees Celsius is needed for the fusion reaction to take place. Although deuterium is available naturally in large quantities from the oceans (but requires a very complex extraction process), tritium must be prepared artificially, since it is only found in very small quantities in the natural world.

In November 2017, the ITER project passed the halfway point to the first plasma. By May 2020, the project's progress to the first plasma was at 70%. The first plasma is scheduled for December 2025. This will be the first time the machine is powered up.

Nuclear fusion is interesting because it can potentially produce much more energy than fission for the same mass of fuel. However, even though the results are conclusive, it will not be possible to exploit them industrially before the second half of the 21st century.

Box 1.7. *Prospects for nuclear fusion: the International Thermonuclear Experimental Reactor (ITER) project*

1.8.3. *Distribution and commercialization of electricity*

Distribution is a very important part of the electrical system.

At production site outlets, transformers change the voltage of alternating current – generally used in modern electrical networks – into high, medium or low voltage. The electrical distribution network consists of five main elements:

– the outlet station of the power plant with the transformers that increase the electrical voltage for transport over high-voltage lines to minimize the loss of power;

– the high-voltage lines themselves;

– substations in which the voltage is lowered for medium-voltage transmission;

– the medium-voltage distribution lines;

– transformers, which then decrease the voltage to the level used by the consumers' equipment.

Therefore, each phase of the network can operate at the appropriate voltage.

To transport electrical current over long distances, high-voltage lines are used to limit losses. Power is the product of voltage and intensity ($P = U \times I$), so the higher the voltage, the lower the intensity needed for the same power. Losses are reduced because they are proportional to the square of the intensity (power dissipation = $R \times I^2$, R being the resistance). This also means that fewer lines have to be used and, since the size of the network is smaller, its environmental footprint is reduced.

Alternating current is easier to use for:	**Direct current is required for:**
– Electricity generation even in high-capacity power plants – Voltage change in transformers – Prevention of short circuits	– Submarine transmission over long distances (around 30 km at 400 kV) – Transmission over very long distances (over 600–800 km for 1,000 MW power) to limit losses associated with AC transmission – Asynchronous links between networks of different frequencies (e.g. the interconnection between Great Britain and France where, although the two countries operate at 50 Hz, the networks are not synchronized) – Limiting the number of conductors (two wires instead of three)

Table 1.3. *Alternating current and direct current*

In the French electricity distribution network, the lines used have the following voltages:

– The domestic power network is supplied at a low voltage of 230 V.

– At the neighborhood level, the network is supplied at 20 kV. Small and medium industries, shopping centers, commercial superstores, major local authorities, hospitals and schools are connected to the medium voltage network. These institutions and businesses have access to power of several hundreds or thousands of kW and account for nearly one-third of national consumption.

– Regional transport is powered by lines whose voltage varies from 63 to 90 kV.

– Finally, transport at the national level is powered by lines of 225 or 400 kV. The major industrial consumers, for example chemical industries, steelmaking and metallurgical plants, railways and the RATP (Paris Transport Authority), which account for nearly one-third of the country's electricity consumption, are connected to this network.

The 400 kV lines that connect the distribution networks of different countries are known as international interconnection lines. They serve a dual function: providing mutual backup between countries and providing a means for international trade in electricity which favors the operation of power plants with the lowest cost at the expense of those with the highest cost.

The interconnected networks are complex and large: they include parts controlled by different operators and enable significant savings to be made. To protect against electricity blackouts, hospitals, public buildings and other facilities for which continuous electricity supply is crucial all have backup generators (blackouts are most often caused by distribution networks or even regional transport networks).

1.8.4. *Electricity: end-use*

Electricity serves a very wide range of needs. At present, only non-rail transport is still a captive customer for petroleum products (a major part of rail transport is now powered by electricity).

In the automotive transport sector, hybrid cars (combining internal combustion engines and electric motors) and 100% electric vehicles are rapidly gaining ground. Hybrid cars run either on petroleum-based fuel or on electricity generated when the vehicle changes speed. Some hybrid vehicles are also rechargeable. The worldwide fleet of electric vehicles (hybrids and fully electric vehicles) has grown from 112,000 in 2012 to 26 million in 2022. The main users of electric vehicles are

China, the United States, Norway, Germany and Japan. China is both the biggest manufacturer of electric vehicles and the biggest buyer. Government initiatives, such as subsidies for new electric vehicles (NEVs) and tax relief policies, are encouraging Chinese automakers to rapidly ramp up electric vehicle production.

Electricity consumers can be classified according to the type of energy that results from the different uses of electricity:

– Mechanical use: motors and machines;

– Thermal use: heating buildings or water;

– Household appliance use: alarm clocks, vacuum cleaners, computers, refrigeration and air conditioning;

– Radiant use: lighting (residential, industrial or public spaces), lasers, radar and radio-frequency emissions like radio, television, telephones, etc.;

A single device may use several forms of electrical energy simultaneously: a computer uses mechanical energy to operate the hard disc and cooling fan, as well as radiant energy for the monitor.

End-uses of electricity can also be classified by categories of consumers; i.e. the industrial, commercial and institutional, residential and transport sectors.

Thermal electricity generating plants have low efficiencies: roughly 40% for coal-fired or fuel oil power plants and 60% at best for gas-fired combined cycle power plants. The rest of the energy is lost in the form of heat. This has led to the idea of so-called cogeneration power plants, which simultaneously produce heat and electricity. The heat must of course be used nearby.

> Combined heat and power or cogeneration units allow for optimal management of natural resources, since they can result in efficiency of the order of 80–90%. A gas turbine equipped with a recovery boiler can produce roughly 35 megajoules (MJ) of electricity and 50 MJ of heat from 100 MJ of fuel. If the same quantities of heat and electricity were produced separately, consumption would be roughly 90 MJ of fuel for the generator set and 55 MJ for the boiler or a total of 145 MJ. In this simplified example, cogeneration results in a fuel savings of more than 30%.

Box 1.8. *Cogeneration*

1.9. Renewable energy

Renewable energy is derived from the major forces that operate on our planet, i.e. sun, water, wind, etc. It also includes wood. Such energy is inexhaustible, at least over a very long timescale. Historically, renewable energy was the first energy source used by humankind; until the end of the 17th century wood was the most widely used energy source.

We discuss the different types of renewable energies in greater detail in Chapter 2, which is devoted more specifically to the energy transition.

1.10. Oil: the reference energy

Oil remains the reference energy because it presents several essential characteristics. It is a liquid, concentrated form of energy that is easy to produce, transport and distribute.

1.10.1. *The characteristics of oil*

Oil has several essential characteristics.

1.10.1.1. *A strategic raw material*

Much of our civilization is based on the transport of individuals or goods. In addition, passenger cars operate mainly with gasoline or diesel fuel, trucks with diesel fuel and planes with jet fuel. Oil is therefore indispensable in the transport sector, even though the development of electric vehicles is rapid and the use of other fuels (gas) is possible.

Oil is a major source of fuel in a war. The importance of oil became apparent before and during World War I. In 1914, Winston Churchill, British First Lord of the Admiralty, committed the Royal Navy to the use of heavy fuel oil rather than continuing with coal as its fuel. This was an important decision, as the UK is rich in coal but has no oil. However, the use of oil conferred an irrefutable advantage in terms of speed and ease of use, which was essential for maritime conflicts. During World War I, tanks and motorized vehicles, few in number in 1914 (horses were still used to pull heavy weapons), played an essential role in the final months of the conflict. Fighter planes also made their appearance in the final months of the conflict.

1.10.1.2. *"Oil is liquid"*

This famous sentence spoken by the economist Paul Frankel may seem trivial, but this characteristic makes oil an energy that is easy to produce, transport and use. In addition, oil is a concentrated energy source: gas is much more costly to transport and distribute, coal is a solid which is more difficult to handle and electricity is also an energy that is costly to produce and very difficult to store. This ease of production means that oil trading dominates world trade in terms of both volume and value: depending on the price of crude oil, oil transactions can represent 2–4 trillion dollars per year. The oil market is global since oil can be easily transported from one part of the world to another.

1.10.1.3. *Oil, a raw material whose price can be much higher than the cost of production*

Oil only costs a few dollars per barrel to produce in the Middle East, and a few tens of dollars at most in more difficult conditions, but the price of oil at the start of the 21st century often exceeds the highest cost of its production. Is this a consequence of its strategic nature? The effect of actual or planned scarcity? Whatever the case, oil is what is referred to as a rent industry: the rent is the difference between the price (which is supposed to represent a fair value for the consumer) and the cost of production.

Economists call the difference between the selling price and the production cost of a raw material a "rent" and often distinguish between differential and absolute rents.

Take wheat for example. If it costs producers with good land $100 to produce a ton of wheat, and producers with less good land $300 to produce a ton of wheat, and if wheat costing $300 to produce is needed to meet consumer demand, the price should rise to $300. A producer able to produce at a cost of 100 dollars will benefit from a differential rent of 200 dollars (300 – 100). If, for reasons linked to market pressure, the price reaches 400 dollars, all producers will benefit from an additional absolute rent of 100 dollars (400 – 300).

Currently, in the case of oil, the cost of production (depending on the zone) is approximately between 5 dollars (Saudi Arabia, some even claim a lower cost) and 40 dollars per barrel (in rare cases it may be slightly higher) for a selling price of around 80 dollars. The absolute rent for all producers is therefore 40 dollars (80 – 40), with Saudi Arabia receiving an additional differential rent of 35 dollars (40 – 5).

In most oil-producing countries, and in particular in OPEC, the sale of oil is the main source of government revenue. The price needed to balance the budget (equilibrium price) is high. This explains why the price of oil often remains well above the cost of production.

Box 1.9. *Oil income and rent*

In Saudi Arabia the cost of production (excluding capital) is roughly $5 per barrel (some sources cite higher figures), whereas the price of oil has always been higher, even much higher, since 2000. This rent goes to the state, which returns a portion of it to the national company, Saudi Aramco, which holds the monopoly on exploitation of the kingdom's hydrocarbon resources, to finance exploration, production and processing operations. Except in the USA, in countries where private international companies (international oil companies (IOCs): ExxonMobil, BP, Shell, Total Energies, Chevron, etc.) operate alone or in association with a state-owned company (as is the case for Nigeria, Angola, and in numerous producing countries) the rent is shared between the state and the *joint venture* that produces the oil, which involves the national company and the foreign company(ies).

1.10.2. *The origins of oil*

According to the most widely recognized theory, "rock oil" (petroleum or petrol) is formed from microorganisms. Tens of millions of years ago, these microorganisms accumulated in sediments and were then gradually buried in the soil. Under the effect of temperature and pressure, they were transformed into kerogen – immature crude oil – composed of a mixture of large hydrocarbon molecules (Figure 1.7).

When the transformation of kerogen into oil is completed, this oil rises to the surface. There are then two possibilities. In the first stage, the "oil" rises to the surface without encountering an obstacle. The light fractions then either evaporate or are destroyed by bacteria and a residue remains, natural bitumen, whose traces and uses have been recorded in many periods of history (caulking for Noah's Ark and Moses' cradle, bitumen found by Marco Polo in today's Iraq, sources of pitch from the Massif Central in France, and the oil sands deposits of Canada). Alternatively, the oil may encounter a reservoir rock – carbonates, sandstone, compacted sand and corals – and creep into the pores and interstitial spaces of these rocks. Provided the reservoir has an impermeable overburden or cap rock, the oil remains trapped in this rock until the bit from a drilling device allows it to escape.

Quite often, above the layer which contains the crude oil, there is a sedimentary layer whose pores are filled with gas, natural gas mainly composed of methane, which is called associated gas (associated with the crude oil). Other deposits – similar in many points – will only contain what is known as "dry" gas, i.e. there will be no liquid hydrocarbons in the reservoir. This results from different conditions from those giving rise to the formation of heavier hydrocarbons, for example a higher temperature. Under the sedimentary layer(s) containing the crude oil and/or gas, there is another sedimentary layer that is water-saturated.

Crude oil and natural gas are mixtures of hydrocarbon molecules. As the word hydrocarbon implies, each molecule is composed of atoms of carbon and hydrogen.. Crude oil includes molecules that range from the simplest, methane, with just one carbon atom, to very heavy molecules that contain 20 to 30 or more carbon atoms. Natural gas – whether associated or dry – mainly consists of methane and also contains variable proportions of heavier molecules.

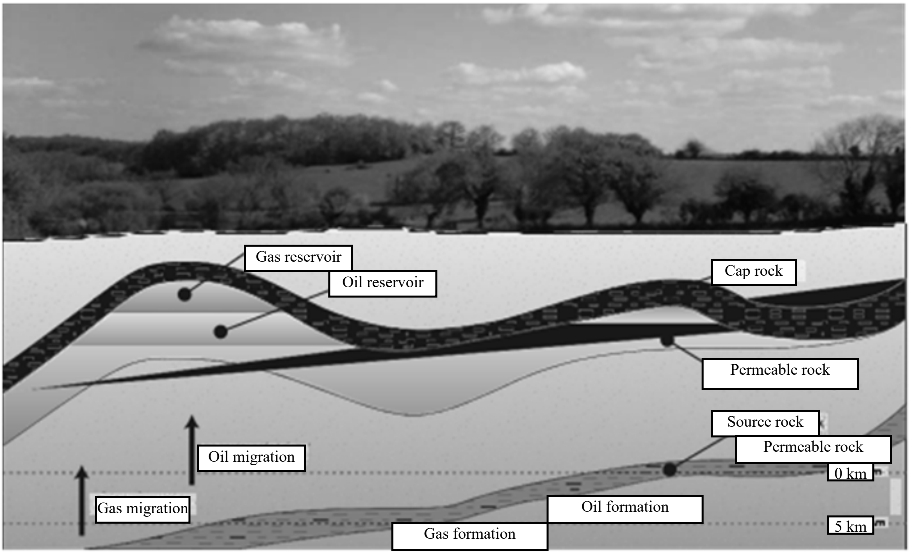

Figure 1.7. *Formation of oil. For a color version of this figure, see www.iste.co.uk/favennec/geopolitics1.zip*

To simplify, there are three types of hydrocarbon deposits: oil deposits covered by associated gas, oil deposits without associated gas and "dry" gas deposits with no liquid in the reservoir.

When natural gas emerges from underground, the decrease in temperature and pressure causes the heavier molecules present in the gaseous state in the reservoir to condense. These heavy fractions are called condensates or natural gas liquids (NGLs). A condensate is therefore a very light petroleum which, on distillation, will provide a high proportion of gasoline and diesel fuel.

The nomenclature has not been fully established, but for users – who are above all interested in the gasoline and diesel they buy at the pump – these distinctions are not very important. All of these "liquids" can be transformed into fuel or combustible material.

Different categories of oil

1) Conventional oil: each deposit or field contains a different crude oil, meaning that there are in fact 400–500 different qualities of crude oil, whose specific gravity – density – varies from roughly 0.8 to 1. A conventional crude oil can be produced with traditional processes. When they are refined, the lightest, i.e. those with a density close to 0.8, mainly provide gasoline and diesel fuel (the highest value products) while the others will mainly provide heavy fuel oil. The condensates (light liquids associated with natural gas

production) correspond to a very light conventional oil that provides a large proportion of gasoline and diesel fuel.

2) Unconventional oils:

- very heavy or extra-heavy oils and oil sands, which are mainly concentrated in Canada and Venezuela. They require specific production and transformation processes in order to be transformed into synthetic crude oils that can be used in refineries;

- oil shale, i.e. rocks that contain organic matter whose conversion into hydrocarbons is not complete. Extracting this oil is both extremely costly and highly damaging to the environment. It has been abandoned;

- liquids obtained via the chemical transformation of coal, gas or biomass (gas to liquid (GTL), coal to liquid (CTL), biomass to liquid (BTL));

- biofuels;

- shale oil, light oil in very low-porosity rock produced by hydraulic fracturing. A similar type of oil is found in low-porosity deposits. These are now known as light tight oil (LTO). LTO is mainly produced in the United States and accounts for around 5% of total world production.

Box 1.10. *Different categories of oil*

1.11. From oil exploration to oil marketing

1.11.1. *Oil exploration*

Initially, geologists search for clues that might indicate the presence of hydrocarbons. Next, geophysicists proceed with seismic techniques that send sound waves from the surface to the depths of the soil. These waves will be reflected by the interface between ground layers which, after processing of the raw data, enables maps and cross-sections of the subsoil to be prepared. These diagrams, previously in two dimensions, can now be produced in three dimensions (seismic 3D). Seismic 4D has even been proposed, by adding in the time dimension (e.g. seismic projects done on exactly the same zone, but at intervals of several months).

Once the possibility of the presence of hydrocarbons has been assessed with reasonable certainty, exploration drilling takes place. This drilling will be referred to as “dry” if it does not uncover a deposit of hydrocarbons (gas or oil). In case of success, where indications of oil or gas are found, in many cases, more extensive drilling must take place to assess the volume of reserves and whether the deposit has commercial potential.

1.11.2. *Oil production*

Production from oil (or gas) deposits is developed by drilling several producer wells (Figure 1.8). The flows from the various wells are collected by a network of pipes and directed to processing facilities where the crude oil is "stabilized". Stabilization means separating the gaseous and liquid fractions to permit transport of the oil safely. If the crude oil were not degassed, it would give rise to a high risk of explosion.

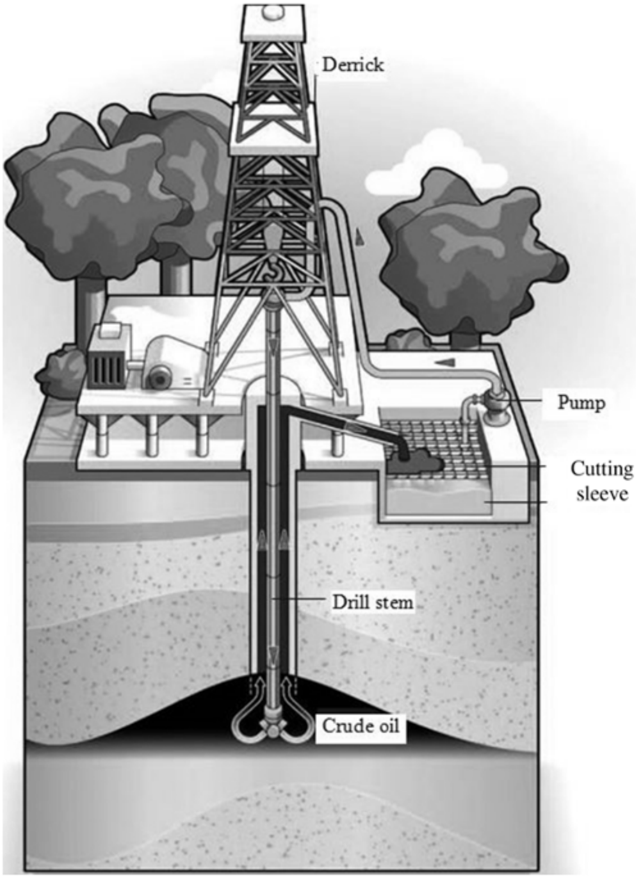

Figure 1.8. *Drilling*

If production is onshore, the liquid crude oil will then be routed either directly to a refinery that may be either close or some distance from the oil field[1] or to a marine terminal where it will be loaded onto tankers to be shipped to consuming regions.

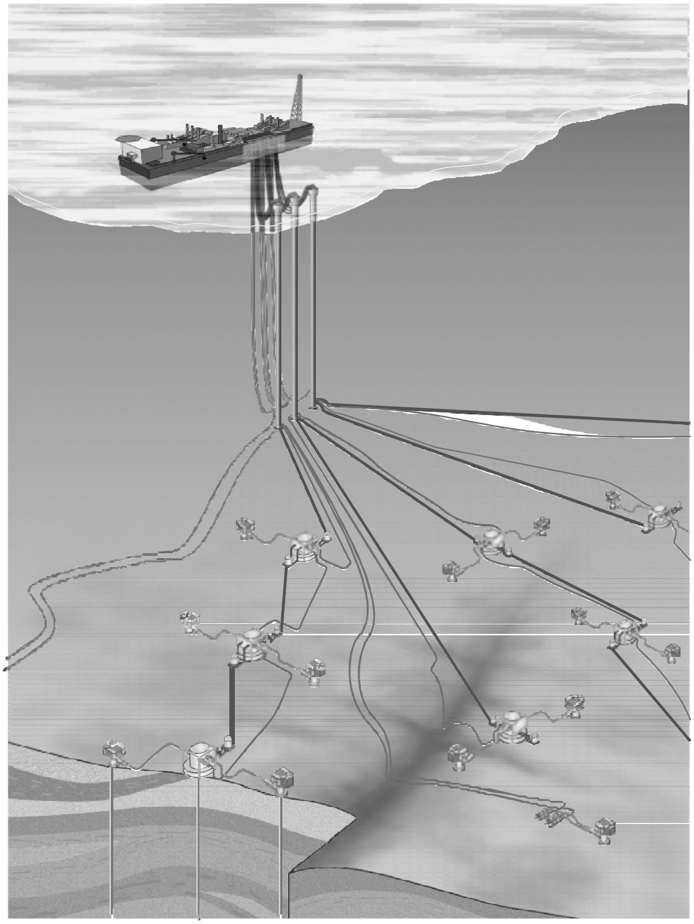

Figure 1.9. *Example of offshore oil production*

1 The crude oil produced in some inland American states is routed over several miles via pipes (or by truck in the case of stripper wells or marginal wells) to nearby refineries where it is processed. In Russia, crude oil from Western Siberia can be routed over thousands of miles to refineries in the region of Moscow or the Ukraine. Within the framework of the "socialist division of labour" and to avoid concentrating production and processing activities in the same region – which would give it major strategic power – Stalin ordered the construction of very large refineries in regions lacking in crude oil.

If production is offshore the crude oil may be processed above the oil field on platforms carrying separation facilities, then sent to the coast via pipelines (in the North Sea, this is the case for Brent crude oil which is stored and loaded on ships at Sullom Voe, the Shetlands Islands Port). It can also be stored on a platform which includes production, storage and shipping facilities. This type of platform is referred to as floating production, storage and offloading (FPSO). This involves an extremely large barge (usually made of steel, but sometimes made of concrete) connected to pipes that bring up the crude oil from undersea deposits. This is where the oil is stored, and where the ship will dock to take delivery of the crude oil (Figure 1.9).

1.11.3. *Oil transport*

Crude oil may be transported entirely via pipelines (this may be necessary if imposed by the location of the production fields and the refinery) or by ships. Over long distances – greater than several thousand miles – transport by large ships is generally more economic.

The size of ships used to transport crude oil varies from several thousands to several hundreds of thousands of tons. The capacity of oil tankers has significantly increased over time. It especially increased between 1945 – when it did not exceed 15,000–20,000 tons – and the start of the 1970s, when several tankers of more than 500,000 deadweight tons (dwt) were built. This increase was made possible by progress in construction techniques, which resulted in economies of scale and met the needs of a significant increase in consumption in the 1950s and 1960s.

By decreasing the demand for oil and favoring production in zones close to consuming countries, the oil shocks reduced the advantages of very large tankers, which also required special and costly facilities to accommodate them.

Currently, the main types of tankers used are as follows:

– Ultra-large crude carriers (ULCCs), which are larger than 320,000 dwt (deadweight tons), with 1 dwt being roughly 1 ton of cargo;

– Very large crude carriers (VLCCs), which are tankers from 160,000 to 320,000 dwt, used to transport large quantities of crude oil over long distances, particularly from the Middle East to the United States, Europe and the major consumers of Asia;

– Suezmax tankers for transport via the Suez canal, which are 120,000–160,000 dwt;

– Aframax (80,000–120,000 dwt) and Panamax (60,000–80,000 dwt), etc.

Another classification, used by specialists, is as follows:

– general purpose: 16,500–24,900 dwt;

– medium range: 25,000–44,900 dwt;

– large range 1: 45,000–79,900 dwt;

– large range 2: 80,000–159,900 dwt;

– VLCC: over 160,000 dwt.

Petroleum products are generally transported in smaller ships, simply because the quantities to be transported are lower. However, the development of export refineries capable of producing hundreds of thousands of tons of gasoline or diesel has led to the transport of products by large vessels.

Typically, the barges that ship end-products manufactured in Rotterdam down the Rhine to Germany, Switzerland or France have a capacity of 1,000–3,000 tons.

While a large proportion of oil is transported by ship, other means obviously exist.

Oil and gas pipelines have been particularly developed in North America and Europe but traverse all continents and, on a worldwide scale, total roughly 1.2 million miles in length. Although sometimes located offshore, pipelines are mainly ground-based, built either on the ground or buried at a depth of several yards for safety reasons. Depending on the zones crossed, they will include varying degrees of insulation, protection or even heating. Highly capital-intensive, it is essential for pipelines that the zones they cross be secure. They create relationships of economic dependence between countries, as reflected by throughput tariffs that may equate to several percentage points of the value of the oil transported.

Rail transport is rather important. Therefore, between China and Russia, several hundred thousand barrels are transported daily by rail. In Iraq, although most crude oil is exported via pipelines, recent years have seen the transport of nearly 200,000 barrels daily by road tank wagons heading for Turkey, Syria or Jordan .

As an indication, the following figures were recorded for the Indian market in 2011: 52% of oil was transported by pipeline, 18% by boat, 14% by road and 16% by rail (Ganguly 2011). In terms of average cost, transporting one ton of oil over 1,000 kilometers (620 miles) in India costs $17 using a newly built pipeline, $13 if the pipeline is fully depreciated, $37 by road tank wagon and $30 by rail tank car.

Box 1.11. *Different methods for transporting hydrocarbons*

1.11.4. *Oil processing: refining principles and end-uses for products*

It is better to speak of the consumption of petroleum products rather than oil, since all oil is consumed in the form of gasolines, diesel fuels, heavy fuel oils, etc. Crude oil is transformed into these end products in refineries, made up of groups of processing units.

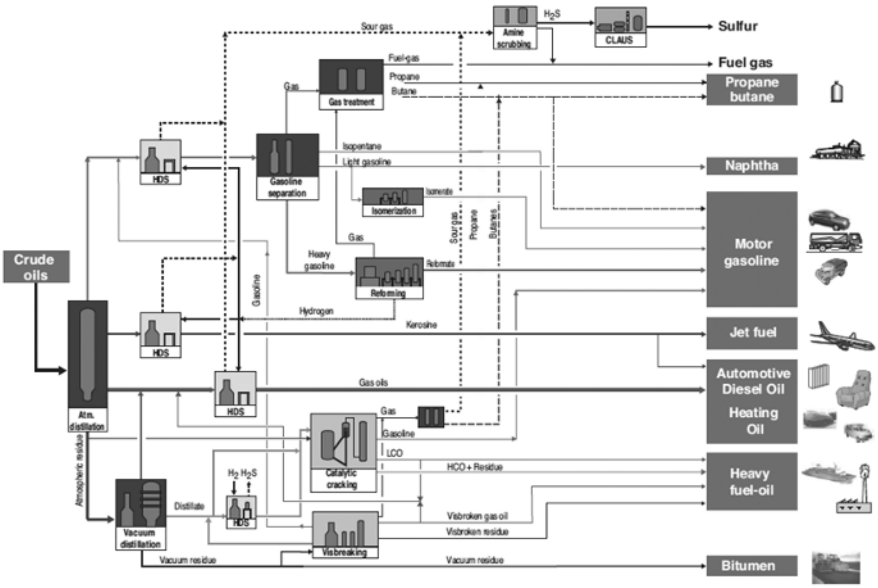

Figure 1.10. *Refinery flow chart*

The first of these is the atmospheric distillation unit, which separates the crude oil into various cuts (light, medium or heavy) which, after upgrading, will result in commercial products (Figure 1.10):

– Light cuts include liquefied petroleum gas (LPG; propane and butane), automotive gasolines and naphtha, a raw material needed for the manufacture of basic petrochemical products.

– Medium cuts include jet fuel, diesel fuel and domestic heating oil.

– Heavy cuts include heavy fuel oil, bitumen and lubricating oils.

– Other process units make it possible to improve product quality and to reduce the production of heavy fuel oil, the demand for which is declining, through conversion or cracking into light products.

1.11.4.1. *Automotive fuels: gasoline and diesel fuel*

The internal combustion engines that powered most automobiles (up to recently) have either been spark ignition engines (which use gasoline) or diesel engines (which use diesel fuel). In Europe and many other countries, diesel fuel has long been in high demand, as diesel engines are more efficient than petrol engines and consume less fuel. The affair called “Dieselgate” refers to the actual pollutant emissions of vehicles, which often turn out to be much higher than the figures announced by carmakers. This has reduced demand for diesel vehicles, which could soon be banned in many cities. In the United States, most cars and a significant number of small transport vehicles operate with gasoline.

Land vehicle fleet and operating modes

The world’s vehicle fleet stands at around 1.5 billion units and is growing by almost 100 million units a year.

The majority of the world’s motor vehicles are still powered by petroleum products such as gasoline or diesel.

However, the progress of electric vehicles is impressive. There are almost 40 million electric vehicles in the world, and growth is running at over 10 million a year, with more on the way. Two types of electric vehicles have been developed. First, hybrid vehicles are equipped with a combustion engine (petrol or diesel) and a small electric motor. Electricity is generated during certain periods of vehicle operation and can power the small electric motor. Then there are the “all-electric vehicles”, equipped with high-capacity batteries. Vehicle range, limited at first, is improving and can now reach several hundred kilometers. However, the size, weight and cost of the batteries remain a handicap. The very high consumption of metals in the construction of these vehicles is a further constraint. Specialists hope to improve battery capacity and reduce costs. Electricity enables motor vehicles to reduce pollution, and several cities around the world are strongly encouraging their use because of growing health concerns about air pollution:

Other energies can be used to power motor vehicles. The use of alternative fuels is on the increase worldwide, particularly in Europe.

For cars, the following alternative fuels can be considered:

– LPG, or liquefied petroleum gas, contains mainly butane, sometimes mixed with propane. Replacing petrol with LPG requires very little adaptation. LPG is an excellent fuel and less polluting than petrol (or diesel). However, LPG availability is limited.

– CNG or compressed natural gas (also known as “vehicle natural gas”). Natural gas, or methane, is an excellent fuel but, even when compressed, range is limited and, in most cases, it will be used in combination with gasoline (in fuel-powered vehicles, gasoline is used when the natural gas has run out). However, given the very large reserves of natural gas, the use of CNG as a fuel has the potential to develop in many countries.

– Biofuels: ethanol or vegetable oil, see Chapter 2.

– LNG: liquefied natural gas can – since it is methane – be an excellent fuel. The problem is the product's very low liquefaction point (–162°C). However, new regulations concerning the sulfur content of fuels used by ships (enacted in 2020 by the International Maritime Organization) stipulate that sulfur content must be less than 0.5%, a specification that is very difficult for traditional fuels to achieve. This will encourage the development of LNG as a fuel for large ships. This would also help to contain the very significant pollution associated with cruise ships when they are in port.

– Hydrogen: any vehicle can use a fuel cell, a device that combines hydrogen and oxygen to produce electricity and extremely pure water. The electricity powers an electric motor. The key problem is hydrogen production and storage. Production is still mainly achieved by so-called steam reforming of hydrocarbons, releasing CO_2. The electrolysis of water using electricity from solar panels or wind turbines could be a solution. Storage also remains a major concern, given the number of explosive accidents. However, some countries are investing large sums of money in the development of hydrogen as an automotive fuel.

A number of alternatives, some of them very costly, exist that could replace petroleum products as fuels for most mobile engines, with the exception of aircraft. An electric aircraft capable of carrying 100 or 200 passengers will remain a dream for many years to come.

Box 1.12. *Transportation alternatives*

With 5% of the global population, the USA consumes nearly 50% of the automotive gasoline used throughout the world. Automotive gasoline also represents nearly 50% of the total demand for petroleum products in the USA. Why such a demand? First, because the development of the petroleum industry started in the USA. Next, this is also the country where the development of the automobile industry has been greatest, and transport needs are particularly important in this very large country. In contrast to the situation in Europe, diesel use has always been limited to big trucks. Most of the light duty vehicles (traditional cars) use gasoline.

1.11.4.2. *Jet fuel*

An intermediate product (by density) between gasoline and diesel fuel, jet fuel is definitely the product for which consumption is increasing the fastest, due to the strong growth in air transport. Jet fuel must of course remain liquid at temperatures in the order of 50°C, close to those encountered in the upper atmosphere.

1.11.4.3. *Heating fuel oils*

A significant quantity of oil continues to be consumed in the form of fuel oils: domestic heating oil (also called home heating oil or light fuel oil) and heavy fuel oil.

Domestic heating oil is mainly used to heat residential homes and commercial buildings, but it is also used in agriculture and by fishing boats. The high consumption of domestic heating oil in the major industrialized countries significantly decreased after the oil shocks and remains low. This product has largely been replaced by natural gas.

The consumption of heavy fuel oil has developed similarly: in the 1960s, it was rapidly substituted for coal in many industrial applications, including the production of electricity. However, in the 1980s, the strong increase in its price along with the oil shocks resulted in its replacement by gas and coal in industry, and by the same products plus nuclear energy for the production of electricity. In most countries, consumption of heavy fuel oil is decreasing relentlessly, with the market being increasingly limited to that of bunker fuel oil. Heavy fuel oil remains the fuel for the large diesel motors that power major transport ships. However, new regulations concerning sulfur content are likely to further reduce outlets.

1.11.4.4. *Liquefied petroleum gas (LPG)*

LPG is propane and/or butane. The name comes from the fact that, at ordinary temperatures, they are in a gaseous state, but they can be maintained in a liquid state under moderate pressure. They are therefore sold in the well-known bottles (12 kg, 6 kg or even less).

There are two sources of LPG: the propane and butane recovered during the production of crude oil or natural gas and the propane and butane recovered at the refinery. Altogether, roughly 60% of LPG available in the world comes from the production sector and 40% from refining.

World production of LPG is roughly 300 million tons p.a. With similar characteristics, natural gas and liquefied petroleum gas also have similar markets. LPG is mainly used for cooking and heating, either alone or as a complement to natural gas. It is also used as an industrial fuel in sectors that require a very clean type of fuel. LPG is also used in transport as a replacement for gasoline, thereby reducing pollutant emissions.

1.11.4.5. *Condensates*

Condensates are liquid fractions produced in association with natural gas by condensation during production. They are also known as natural gas liquids (NGLs).

The production of condensates is increasing strongly with the rapid development of natural gas production. Light condensates can be directly used as feedstock in the petrochemical industry, but heavy condensates must be treated in refineries in order to extract gasoline, diesel fuel and other products. Due to their characteristics, a condensate cannot be processed in a traditional refinery. Several specialized refineries have been or will be constructed, but the majority of production is mixed with other crude oils for transport and subsequent processing.

1.11.4.6. *Naphtha and petrochemicals*

Petrochemicals are omnipresent in our lives. They are used to produce plastic materials, synthetic fibers, drugs, solvents, perfumes, fertilizer, insecticides, etc.

The petrochemical industry is based on two basic processes. Steam cracking brings naphtha (or in some cases LPG or middle distillates) to temperatures that are far higher than those used in other refining processes, of the order of 900°C. Steam cracking mainly produces olefins, particularly ethylene and propylene, as well as heavier streams (e.g. steam-cracked gasoline) which contain aromatics including benzene. Another process – catalytic reforming – provides aromatics, which are base molecules that along with ethylene and propylene undergo polymerization (the molecules become linked) to produce plastics, synthetic fibers and synthetic rubbers, which we are all familiar with.

The proportion of oil used as a raw material for petrochemicals only represents some 12% of world oil production. However, the added value is high.

1.11.5. *Marketing and distribution of petroleum products*

Depending on the type of products and the users, delivery and storage will vary significantly. Large users (industry, airports, etc.) are often directly supplied by refineries using pipelines, inland waterways or rail. Road transport fuels sold in service stations follow a more complex route. They are transported as above from the refinery to a storage depot and from there by road tank wagon to the service stations. The latter requires very good logistics and has proven to be costly (two-thirds of jobs in the oil sector are in this last stage).

For the past 20 years, in Europe, companies have been streamlining their distribution network by reducing the number of their service stations, concentrating them on major traffic routes and expanding the services they offer, to fight competition from new entrants, particularly the hypermarkets, which have won a large market share in many countries. In developing countries, there is still a fair increase in the consumption of motor fuels and in the construction of service stations.

1.12. Natural gas

Natural gas, like oil, consists of hydrocarbons, but contains a higher proportion of hydrogen and a lower proportion of carbon. Therefore, using natural gas to generate electricity means emitting 50% less CO_2 than using coal and roughly 30% less CO_2 than using oil. The electricity yield is 60% in CCGTs versus barely 40% for other thermal fuels such as coal, heavy fuel oil, etc. Natural gas is the main source of electricity generation in North America, the CIS, the Middle East and Africa.

The geography of gas production is very different from the geography of oil production. While the cost of transporting oil represents only a small part of its price, the cost of gas transport and distribution is very high. Natural gas can be transported by gas pipeline or by ship following liquefaction (LNG chain). The vessels are called methane tankers or LNG carriers. In the case of a pipeline, the same pipeline can transport five to ten times more energy in liquid form (oil) than in the form of gas. Trade is therefore subject to the constraint of proximity, and it is harder to speak of a worldwide price for this product. Furthermore, the nature of the supply, via gas pipeline or LNG, greatly affects prices. Hence, for example, Japan pays more for its gas, since it must be imported in methane tankers.

Therefore, for a long period, the gas market remained mainly regional and several trade zones developed relatively independently from one another (North America; Europe with suppliers coming mainly from Russia – before the invasion of Ukraine – Norway and North Africa; Asia with supplies from Qatar, Malaysia, Indonesia, Australia, more central Asian countries and Russia). The main gas producers are therefore either consumers (United States, China, Russia) or countries that are close to major consumers (Canada for the United States; Norway and Algeria for Europe; Malaysia, Indonesia, Australia and Qatar for Asia). Demand for natural gas has grown considerably in the United States and China in recent years.

1.12.1. *Natural gas: exploration and production*

The formation of natural gas is analogous to that of oil. The evolution of microorganisms into either liquid (crude oil) or gas (natural gas) mainly depends on temperature and pressure conditions.

The cost of producing gas is generally lower than that of oil: once wells have been drilled, gas rises spontaneously from the reservoir. Furthermore, when it is "associated" with oil production, its production cost may be considered to be zero

– or nearly so – since both the capital and operating costs are primarily incurred to produce the oil.

1.12.2. *Natural gas processing*

Raw gas from reservoirs is processed to remove the major impurities and heavy fractions. Natural gas is mainly composed of methane, but it also contains varying proportions of ethane, propane, butane, etc. It can contain significant proportions of CO_2 and nitrogen, which must be eliminated as they reduce the calorific value. Lacq gas, discovered in France in 1951, contained high proportions of H_2S (hydrogen sulfide), which had to be eliminated for reasons of pollution and corrosion.

Processing consists of recovering most of the propane and butane, as well as the heavier fractions.

1.12.3. *Natural gas transport*

Natural gas can be transported by pipeline or in liquid form on ships specialized in the transport of LNG or in methane tankers.

Transport by pipeline remains the preferred method, particularly over short distances. It is more economical than the LNG chain, which only becomes competitive beyond several thousand miles (Figure 1.11). Used to transport gas over long distances, a gas pipeline must be resistant to the high pressure (exceeding 150 bars) provided by compressor plants located throughout the route (every 30–120 miles), permitting the gas to be transported at speeds of tens of miles per hour (mph).

The number of compressor plants and their power depends on the resistance of the gas pipeline and that depends on its diameter, which may reach 120 cm (50 inches).

Transport by ship requires that the natural gas be liquefied. To do this, the temperature of the gas must be lowered to −162°C, the liquefaction temperature of methane. This operation is extremely expensive. A liquefaction plant generally includes several parallel units (trains), and each train can process up to several billion cubic meters of gas per year. Therefore, Qatar now has LNG trains with a unit capacity of 8 Mt/year.

The liquid gas is then loaded onto a specialized ship, called a methane tanker. For a long time the capacity of a methane tanker was of the order of 100–150,000 cubic meters, but today, it may reach 260,000 cubic meters. Of course, the liquid gas must be regasified upon arrival in the consuming country, to be introduced into the mass transport network.

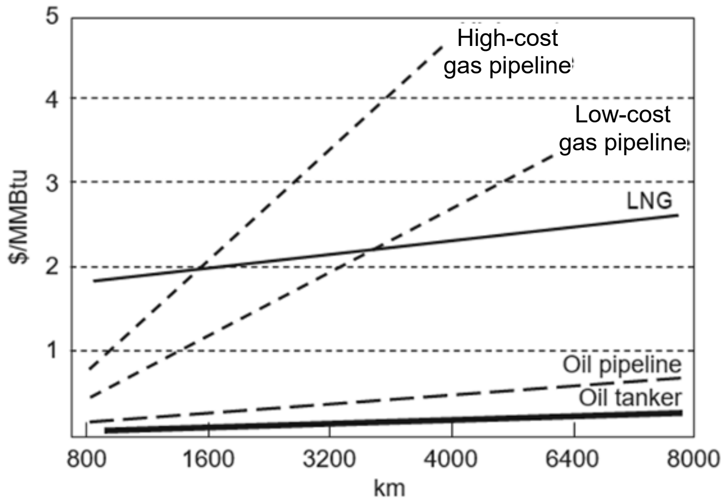

Figure 1.11. *Gas transportation costs: pipelines versus LNG (source: IFP énergies nouvelles)*

1.12.4. *Use of natural gas*

The first gas used on a large scale was town gas, simultaneously discovered at the end of the 18th century by the Frenchman Philippe Lebon and the Englishman William Murdoch. This gas is produced by pyrolysis of hard coal or wood, i.e. heating it to a high temperature in the absence of air. Up to the mid-19th century, it was mainly used to light streets and buildings; then other uses, such as heating, were developed.

After 1880, the development of electricity slowed growth in the use of town gas, which came to a halt around 1929 with the Great Depression.

Natural gas then took over from town gas, principally in the USA, from the start of the 20th century. Its use would remain marginal in the rest of the world until World War II. In France, town gas manufacturing plants still existed in the 1960s (the last one at Belfort closed in 1971). However, the discovery of the natural gas deposit in Lacq in 1951 encouraged rapid development of natural gas. The same situation occurred in Italy with the reserves of the Po Plain and, in the Netherlands, with the Groningen deposit (discovered in 1960, it allowed the Netherlands to export natural gas throughout Europe).

Natural gas is a fuel that can be used in most sectors where the production of heat is needed, the so-called residential and commercial sector for cooking and the heating of buildings, the industrial sector and the electricity generation sector.

Compressed natural gas (CNG) is used to power internal combustion engine vehicles in the Asia–Pacific region (Singapore, Malaysia, China, Pakistan, India), in Iran and Egypt and in some South American nations such as Brazil and Argentina. CNG is increasingly used to power buses, trains, cabs, tuk-tuks and vans in developing countries. In Delhi, India, all commercial passenger vehicles must now run on CNG, by government decree, in a bid to reduce air pollution.

Finally, natural gas can be used to produce methanol, a basic raw material used in the manufacture of many chemical compounds. Currently, its main use nevertheless remains the generation of electricity.

GTL is a process used in the chemical conversion of natural gas, for the production of high-quality liquid petroleum products (naphtha, diesel and lubricants). It is based on the same principle as CTL, which starts by gasifying coal. Then – in both cases – the gas is partially burned, resulting in a mixture of carbon monoxide and hydrogen which is used to synthesize heavy molecules, leading finally to the production of fuels.

In 1923, German chemists Fischer and Tropsch developed a process for producing liquid fuels (gasoline, diesel) from coal (CTL process). This process was used by Germany during World War II to manufacture fuels, as Germany had no oil deposits.

In the 1950s, South Africa built a coal liquefaction plant (the SASOL plant at Secunda) in response to the international community's embargo on oil deliveries to combat apartheid. In the same context, South Africa also built a GTL plant: the PetroSA plant in Mossel Bay, in the south of the country.

Due to the abundance of gas, a few new plants have been built, mainly in Qatar and Nigeria.

However, GTL fuels are more expensive to produce than conventional fuels and development of this technology is likely to be limited.

Box 1.13. *CTL, GTL: coal to liquids, gas to liquids*

1.13. Coal

Coal is a mixture of mineral elements, sulfur and nearly pure carbon. Its combustion therefore releases large amounts of CO_2 (and also SO_2 and NO_x). Major efforts are currently underway to make coal "cleaner", both for old and new power plants.

The steam engine was the key factor in the industrial revolution and its use depended on coal. This use of coal marked a dual break: first, the switch from renewable energies (mainly wood) to fossil energies; second, the switch to a system in which energy distribution became a structured industry. It was only by 1800 that coal replaced wood as the main source of energy, and it was in turn replaced by oil as the main source of energy at the start of the 1950s.

Coal is available throughout the world. The main consumers of coal are also major producers (China, the United States, India, etc.), since transport costs are relatively high. More than 85% of coal extracted throughout the world is currently consumed in the country of production.

A clean coal plant has the following characteristics:

– It eliminates sulfur oxides (SO_2) and nitrogen oxides (NO_x) upstream via a circulating fluidized bed and downstream via the processing of exhaust gases.

– It shows improved efficiency: the average efficiency of coal-fired power plants is only 38%. The switch to supercritical cycles can achieve 40–45%, while ultra-supercritical cycles (700°C) can achieve 50%.

– It can operate using co-combustion with biomass.

In summary, the majority of traditional pollution is eliminated and CO_2 emissions are reduced.

Box 1.14. *Clean coal*

Coal production is increasingly concentrated in countries where exploitation is possible at a low cost: open-cast mines or those of shallow depth, with significant reserves. European production – located in deep mines and therefore costly – is strongly declining.

The use of coal is being gradually reduced to the production of electricity and steel. However, it remains the main source of energy for the production of electricity and its consumption continues to grow in this sector (in recent years, coal consumption significantly benefitted from increased oil prices). Nonetheless, there are large differences between geographical zones. A large volume of coal reserves, prices that are lower and less volatile than those of competing energies and "clean coal" technologies all make coal a valuable source of energy source. However, CO_2 emissions should lead to a strong reduction of coal use.

1.13.1. *Origin of coal*

The formation of coal results from the accumulation of plant debris in sediments and its gradual burying under successive layers of material. This process of overlaying deposits gives birth to solid and combustible substances of high carbon content. Depending on how old the formation is, there may be three major categories of fuel: bituminous, lignite or peat:

– *Bituminous coal* was formed 200–300 million years ago, during the so-called Carboniferous period at the end of the Paleozoic era. At that time, the Earth resembled a vast greenhouse, covered with marshes and luxurious vegetation favored by a warm, humid climate. Bituminous coal is the best solid fuel. Compact and black, it has undergone in-depth transformation and no trace of plant life is visible to the naked eye.

– *Lignite*, also known as brown coal, is of more recent formation (Mesozoic and Tertiary eras). It is a fuel of limited calorific value and more polluting.

– *Peat* is found in recent sedimentary formations, is still forming today in peat bogs and is a very mediocre fuel[2].

1.13.2. *Coal production*

Coal is extracted either in open-cast mines or underground tunnels. Choice of the exploitation method depends on the deposit's geological configuration and its environment. If the overburden which covers the layers of coal is not very thick, the deposit is exploited by open-cast mining. If the coal layer is deep, it is mined by digging a network of underground tunnels. This process is complex and costly and may be spread out over 10 years.

Thanks to increasingly complex modern equipment, open-cast mining may be used for deposits under surface layers as thick as 400 meters (1,300 feet). In this way, yields and results are much better than those obtained using tunnels. First, a large surface area must be cleared; the surface layers (which are also called waste rocks)

2 Peat is nevertheless used for electricity generation in the Republic of Ireland, where two peat burning stations were commissioned in 2004/2005.

are removed and the coal is extracted. Waste rocks will be used for backfill during site reclamation. The coal layers gradually appear.

This method has many advantages: working conditions that are less harsh, far greater productivity than that of underground mines, and reduced timeframes for entry into production (2–5 years). Furthermore, since they offer great management flexibility, open-cast mines can adapt better to market demand.

1.13.3. *Coal transport*

Over limited distances, coal is mainly transported by rail and inland waterways. A slurry pipeline may also be used, which is a pipe that carries a suspension of coal in water.

More than 75% of international coal commerce is carried by sea. Most major coal ports have been modernized due to this increasing trade. Coal is carried either by bulk carriers or by mixed cargo vessels that can also transport oil. The larger the capacity of the transporter, the greater the reduction in the cost of sea freight. However, although large cargo loads have increased, there are still small ships for cabotage operations between European countries.

1.13.4. *Coal end-use*

In contrast to oil or gas, coal is a physically stable material and relatively easy to use. However, the extraction and transportation of coal results in significant environmental pollution in the form of fugitive dust (air pollution), soil degradation and groundwater pollution.

The name coal is sometimes reserved for bituminous coal alone. However, there are several qualities of bituminous coal:

– *Anthracite* is highly sought after, but its reserves are limited. It is most widely used for individual home heating.

– *Coking coal* is used for the manufacture of steel. In the blast furnace, iron ore is mixed with coke, which provides the heating and chemical energy needed to transform the ore into molten cast iron, which will then be used to produce steel. The production of a ton of steel requires roughly 600 kg of coke.

– "*Steam*" coal is the main coal used in industrial boilers.

Lignite and peat are used only in electrical power plants and such plants pose serious environmental problems. Like its neighbors, the former Czechoslovakia and

Poland, the former East Germany used enormous quantities of lignite – which has low calorific value but is very rich in sulfur – for the production of electricity. The neighboring forests suffered significant damage because of this. Following German reunification, the use of lignite ceased.

However, the use of coal is strongly defended in the major coal-producing countries (China, India and North America), and its future is linked to the possibility of generating "cleaner" coal, as well as the possibility of CO_2 sequestration.

1.14. Conclusion

Energy demand grows with population growth and rising living standards. There are many sources of energy. Each has its advantages and disadvantages.

Climate change is forcing us to reduce CO_2 emissions, and hence fossil fuel consumption. However, consumption of coal, and above all oil and gas, will remain high for many years to come.