CHAPTER 1

We Need Energy

Energy is a thermodynamic quantity equivalent to the capacity of a physical system to produce work or heat. It is essential to life. If we live better than our primitive ancestors, it is because we use more energy to do work, to produce heat, and to move people and goods. Energy can exist in various forms (chemical, mechanical, electrical, light, etc.). It is in the process of transforming energy from one form to another that we are able to harness part of it for our own use.

BASIC NATURE OF ENERGY

Energy is related to a fundamental symmetry of nature: the invariance of the physical laws under translation in time. In simple words this means that any experiment reproduced at a later time under the same conditions should give the same results. This symmetry law leads to the conservation of the physical quantity, which is energy. There are also other symmetries that lead to important conservation laws. Space invariance with respect to translation or rotation leads, respectively, to conservation laws for momentum and angular momentum. This means that if we translate or rotate an experimental arrangement, we will get the same experimental results. Conservation of energy, momentum, and angular momentum is of basic importance and governs the processes occurring in the universe.

1.1. GENERALITIES

1.1.1. Primary and Secondary Energy

All of the energy sources that we use, except geothermal and nuclear energies, are derived initially from solar energy (Figure 1.1). The fossil fuels that we use today—coal, oil, and natural gas—are derived from organisms (primarily ocean planktons)

Our Energy Future: Resources, Alternatives, and the Environment, Second Edition.
Christian Ngô and Joseph B. Natowitz.

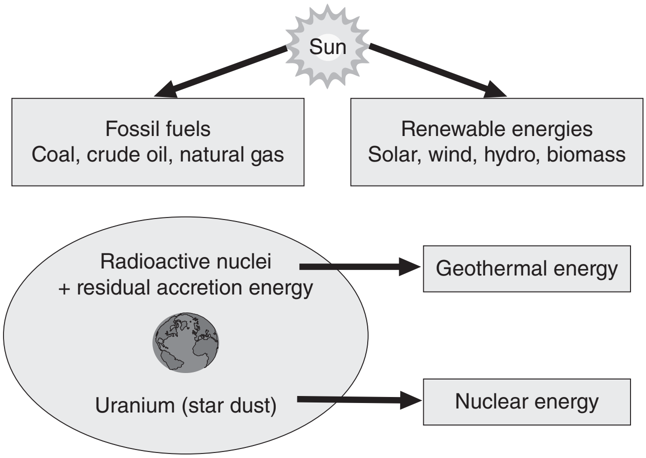

Figure 1.1. Origin of different sources of energy used by humans.

that grew over several hundreds of millions of years, storing the solar energy that reached the earth's surface. Renewable energies—hydro, biomass, and wind—are also directly or indirectly derived from the energy of our sun. Solar and geothermal energy, although technically not renewable are often classified as such because they are effectively inexhaustible on any practical time scale.

Nuclear energy is derived from uranium nuclei contained in the earth. This element was formed in heavy stars and was scattered in space when those stars died. Uranium nuclei were present in the dust from which the solar system was formed about 4.5 billion years ago. The earth formed by accretion of such dust and some thermal energy due to this process still remains. However, most of the thermal energy contained in the earth comes from the decay of radioactive nuclei present in the earth and initially produced in stars.

It is useful to distinguish between primary and secondary energy sources. Primary energy sources correspond to those that exist prior to any human-induced modification. This includes fuels extracted from the ground (coal, crude oil, or natural gas) or energy captured from or stored in natural sources (solar radiation, wind, biomass, etc.). Secondary energy sources are obtained from the transformation of primary sources. Gasoline or diesel fuel from crude oil and charcoal from wood are examples of secondary sources.

We can also distinguish between nonrenewable and renewable energies. Nonrenewable energies are in finite quantities on the earth. Like uranium, which comes from the dust of stars, they could have been present at the earth's formation (about 4.5 billion years ago) or, like fossil fuels (coal, natural gas, crude oil, oil shale, etc.), they could have been synthesized several hundred million years ago. In contrast to the nonrenewable energies, renewable energies will be available as long as the earth and the sun exist, which is estimated to be about 5 billion years.

1.1.2. Energy Units

The ***joule*** is the standard energy unit in the international system. Defined as $1\,\mathrm{kg{\cdot}m^2/s^2}$, it is a very small quantity of energy compared to the amounts we use in daily life. For that reason, we will frequently use another unit widely used in the energy domain: the ***kilowatt-hour*** and its multiples:

$$1\ \mathrm{kWh} = 3.6\times10^6\,\mathrm{J} = 3.6\,\mathrm{MJ}$$

Prefixes defining multiples of any physical quantity are shown in Table 1.1.

For measurements of heat energy, the *calorie* (cal) or its multiple, the kilocalorie, is an older unit that is sometimes still used. One calorie is the quantity of heat necessary to increase the temperature of 1 g of water by 1°C:

$$1\ \mathrm{cal} = 4.18\,\mathrm{J} \qquad 1\ \mathrm{kcal} = 1000\ \mathrm{cal} = 1.16\,\mathrm{Wh}$$

The *British thermal unit* (Btu), also still used on occasion, is defined as the amount of heat necessary to raise 1 pound (lb) of water through 1°F (1 Btu = 1055.06 J).

Use of another unit, derived from the international system, the ***gigajoule*** ($1\,\mathrm{GJ} = 10^9\,\mathrm{J}$), is increasing and is supported by the International Organization for Standardization (ISO). From time to time we will also use this unit.

Two units sometimes used in the United States are the ***quad*** ($1\,\text{quad} = 10^{15}\,\text{Btu}$) and the ***therm*** ($1\,\text{therm} = 10^5\,\text{Btu}$).

A much older unit, the *horsepower* (HP) is still sometimes employed also. It was introduced at a time when animals were the primary source of energy used to work in the fields. By definition 1 HP = 746 W. In fact, this original evaluation of the power of a horse was quite optimistic and corresponds more closely to the power of three horses.

Another unit sometimes employed for very large amounts of energy is the *ton of oil equivalent* (toe). It corresponds to 10 Gcal or 4.1868×10^{10} joules. This is the (accepted) amount of energy that would be produced by burning 1 ton of crude oil. This unit is often used in energy statistics.

TABLE 1.1. Multiple Prefixes

Prefix	Multiplicative Factor	Symbol	Prefix	Multiplicative Factor	Symbol
Deca	10^1	da	Deci	10^{-1}	d
Hecto	10^2	h	Centi	10^{-2}	c
Kilo	10^3	k	Milli	10^{-3}	m
Mega	10^6	M	Micro	10^{-6}	μ
Giga	10^9	G	Nano	10^{-9}	n
Tera	10^{12}	T	Pico	10^{-12}	p
Peta	10^{15}	P	Femto	10^{-15}	f
Exa	10^{18}	E	Atto	10^{-18}	a

The unit toe was defined to answer the following question: Given an energy source, how much oil would be required to produce the same amount of energy? Thus it provides a means for making rough comparisons of the amounts of energy available from different energy sources. This in fact depends upon the nature of the energy produced. It will not be the same for electricity as for heat. It will also depend on the system used to produce the energy as some systems are more efficient than others. Furthermore, the energy content of a ton of oil can vary slightly depending on where the oil comes from. The value quoted earlier has been adopted by convention. Nevertheless, this unit is useful to compare different energy sources.

Conversion equivalents between some common units are shown in Table 1.2.

Some equivalence values of energy sources are given in Table 1.3. The energy content depends very much on the nature of the source. In the case of fossil fuel

TABLE 1.2. Conversion between Selected Units

	MJ	kcal	toe	Btu	kWh
MJ	1	238.8	2.388×10^{-5}	947.8	0.2778
kcal	4.1868×10^{-3}	1	10^{7}	3.968	1.163×10^{-3}
toe	4.1868×10^{4}	10^{7}	1	3.968×10^{7}	11630
Btu	1.0551×10^{-3}	0.252	2.52×10^{-8}	1	2.931×10^{-4}
kWh	3.6	0.86	8.6×10^{-5}	3412	1

TABLE 1.3. Net Calorific Value[a] in Toe of Some Energy Sources

Energy Source	Amount	GJ	toe
Hard coal	1 t	26	0.62
Coal coke	1 t	28	0.67
Lignite briquettes	1 t	32	0.76
Lignite and recovery products	1 t	17	0.4
Crude oil	1 t	42	1
Liquefied petroleum gas (LPG)	1 t	46	1.1
Automotive gasoline and jet fuel	1 t	44	1.05
Petroleum coke	1 t	32	0.76
Ethanol	1 t	26.8	0.64
Biodiesel	1 t	36.8	0.876
Natural gas	1 Nm^3	≈34.9	0.077
	1 MWh (GCV)	3.24	
Wood	Stere (1 m^3)	6.17	0.15
Electricity (nuclear)	1 MWh	3.6	0.26
Electricity (geothermal)	1 MWh	3.6	0.86
Electricity (other)	1 MWh	3.6	0.086
Hydrogen (1 kg $H_2 \approx 11.13\,Nm^3\,H_2$)	1 t	120.1	2.86

Note: For natural gas, the energy is indicated in gross calorific value (GCV). 1 Nm^3, which means one normal cubic meter, is measured at 0°C and 760 mmHg. One has 1 Nm^3 = 0.946 Sm^3, where the standard cubic meter is defined at 25°C and 760 mmHg.

[a] Also called low calorific value.

it may vary depending upon the origin. For example, the gross calorific value of natural gas is equal to about 52.6 MJ/kg if it comes from Norway but only 45.2 MJ/kg if it comes from the Netherlands.

1.1.3. Power

Power is defined as an amount of energy delivered per unit of time. The standard unit is the watt, which corresponds to 1 J/s. In practice, the kilowatt and the megawatt ($1\,\text{kW} = 10^3\,\text{W}$ and $1\,\text{MW} = 10^6\,\text{W}$) are often used. Power and energy should not be confused. In particular, one should not confuse 1 kW (of power) with 1 kWh (of energy). One kilowatt-hour corresponds to the energy of a device, which has a power of 1 kW (e.g., an electric iron) working for a period of 1 h. A 1-kW device that is not functioning does not consume energy.

POWER AND ENERGY

One liter of gasoline contains about 10 kWh of energy. Assume we have 40 l of gasoline at our disposal. The total amount of energy contained is $E = 400$ kWh. Using this gasoline in a car would allow us to drive about 250 mi. At a constant speed of 62.5 mi/h, it would take $t = 4$ h to do that. The power developed would be $E/t = 100$ kW. If, on the other hand, we burn this gasoline in 30 s, the power of the process would be 48 MW.

1.1.4. Energy and First Law of Thermodynamics

It is a basic law of nature that energy is conserved. In other words, energy can neither be created nor destroyed. It can only change form. The first law of thermodynamics applied to the internal energy of a system (which applies to equilibrium states) is just a statement of energy conservation in heat and work conversion processes. The internal energy (U) is a state function, which means that in any thermodynamical transformation the change of internal energy depends only upon the initial and final states of the system under consideration and not on the way in which the transformation is carried out, that is, the "path."

The first law of thermodynamics relates the change of internal energy ΔU to the work W done on the system and the heat Q transferred into the system:

$$\Delta U = W + Q$$

We should note that the convention used in this evaluation is to treat the work done on the system and heat put into the system as positive. Work done by the system and heat removed from the system are designated as negative. In other words, the equation given in the text means that the change in internal energy between two equilibrium states is equal to the difference between heat transfer (Q) *into* the system and work (W) done *by* the system. Work corresponds to an organized energy, while heat is completely disorganized energy since this energy is shared among all the microscopic degrees of freedom of the system. Transforming disorganized energy into organized energy is not an easy task. The reverse operation is much easier. This explains why we never get a 100% yield when extracting work from a heat source.

1.1.5. Entropy and Second Law of Thermodynamics

The first law of thermodynamics tells us whether a process ($A \leftrightarrow B$) is energetically possible, but it does not tell us the direction ($A \rightarrow B$ or $B \rightarrow A$) in which the process can occur spontaneously. In order to answer this question, we have to consider the second law of thermodynamics, which addresses the concept of entropy—a second-state function. At the microscopic level, entropy is a quantity related to disorder. The higher the disorder of a system, the larger its entropy. The unit of entropy is joules per kelvin.

The second law of thermodynamics tells us that the entropy of an isolated system can either spontaneously increase or can remain the same: $\Delta S \geq 0$ for an isolated system. This means, at the microscopic level, that disorder either increases or remains the same.

Thus, the first law of thermodynamics tells us that the total energy of the universe remains constant, while the second law tells us that the quality of the energy constantly decreases. The second law tells us about the direction of irreversible processes. For example, we know from experience that, for an isolated system made of two bodies at different temperature, the heat flows spontaneously from the high-temperature body to the low-temperature one and not in the reverse direction.

At the microscopic level, entropy can be expressed as

$$S = k \ln \Omega$$

where k is the Boltzmann constant ($k = 1.38 \times 10^{-23}$ J/K) and $\ln \Omega$ is the natural logarithm of the number of microscopic states, Ω, available to the system.

In thermodynamics there are several ways of expressing the second law of thermodynamics. One, due to Clausius, is the following: *There is no process in which the only result is to transfer heat from a cold source to a hot one*. It is possible to transfer heat from a cold sink to a hot source, but one needs to provide external work to make this occur. This is the operating principle of refrigerators or heat pumps. A second formulation goes a little further. It is due to Kelvin and Planck: *There is no process in which it is possible to produce work using a constant-temperature heat source*.

During the nineteenth century, steam engines were used to produce work. It was observed that a large part of the energy needed for this purpose was lost in the form of heat. Sadi Carnot, a French physicist, formulated a principle that allowed calculation of the maximum yield for the heat engines that were used at that time. This principle applies generally to any closed system producing work by using two heat sources at different temperatures.

Designate the temperature of the hot source as T_H and the temperature of the cold one as T_C. According to the Carnot principle, the maximum theoretical yield η for producing work in a reversible cycle operating between two heat sources at different temperature is given by

$$\eta = \frac{T_H - T_C}{T_H} = 1 - \frac{T_C}{T_H}$$

1.1.6. Exergy

Contrary to what the name suggests, thermodynamics deals with equilibrium phenomena. However, real processes are often nonequilibrium ones. Here, by equilibrium we refer to the equilibrium of a system with its environment. To better characterize real processes a new quantity, *exergy*, has been introduced. The exergy content of a system indicates its distance from thermodynamic equilibrium. The higher the exergy content, the farther the system from thermodynamic equilibrium and the greater the possibility to do work. Quantitatively, the exergy is the maximum amount of work that can be done during the process of bringing the system into equilibrium with a heat bath (a reservoir at constant temperature). With the same original energy content, it is possible to produce more work if we use a high-temperature source than a low-temperature one.

Assume the following notation: U, V, S, and n are the internal energy, the volume, the entropy, and the molecular or atomic concentration of the system, respectively. The values of these quantities when thermodynamic equilibrium with the environment exists are U_{eq}, V_{eq}, S_{eq}, and n_{eq}; P_0, T_0, and μ_0 are the pressure, the temperature, and the chemical potential of the environment, respectively. Using these quantities the exergy E_x can be defined as follows:

$$E_x = U - U_{\mathrm{eq}} + P_0\left(V - V_{\mathrm{eq}}\right) - T_0\left(S - S_{\mathrm{eq}}\right) - \mu_0\left(n - n_{\mathrm{eq}}\right)$$

For the system there is a driving force toward equilibrium. At constant pressure and chemical potential, the exergy is just the classical free energy of equilibrium thermodynamics. In an irreversible process moving toward equilibrium, the total energy is conserved, but the exergy is not conserved. It decreases as the entropy increases.

1.1.7. Going Back to the Past

Since early times when our ancestors used their own muscles or those of slaves and animals to perform work and improve their living conditions, the quest for new energy sources has been one of history's main driving forces. In practice, most of mankind's energy history has been dominated by renewable energies. This started with the mastery of fire about 500,000 years ago. Making a fire allowed our ancestors to produce heat and light and to cook their meals. Wood was the energy source that was mainly used. It is still widely used today, especially in underdeveloped countries where it is sometimes the only readily available energy source.

Around 3500 B.C., Egyptians used the power of the wind to move boats. The harnessing of this new energy source allowed them to travel greater distances and promote trade with other lands. About 640 B.C., the power of wind was probably also used to grind grain by the Persians, who built windmills in the area that is now Iran. Solar energy was harnessed about 500 B.C. by the Greeks, who developed homes to better use the incoming heat from the sun. Around 85 B.C. geothermal energy was harnessed by the Romans, who used hot springs to heat baths. About the same time running water was also exploited by the Greeks, who used waterwheels to grind grain.

In antiquity, because of an abundant supply of labor, there was not great pressure for development of new energy sources. During the Middle Ages this was less true, and large-scale use of renewable resources such as water or wind developed rapidly. By the eleventh century water mills became very common in countries such as England and France, which had good water resources. The extracted energy was used to grind grain, press olives, operate hammers or the bellows of forges, and so on. Windmills were developed mostly in dry countries like Spain and the Netherlands, where they were used to pump water. In the Netherlands this allowed the retrieval of land from the sea.

The Industrial Revolution, based on mechanization, started around 1750. In this era the steam engine played a key role because it provided power that did not depend upon the flow of rivers or movement of the wind. The first steam engines were used to pump water from coal mines, allowing miners to dig deeper and get more coal. Since the Industrial Revolution energy development has moved swiftly. Fossil fuels (coal, oil, gas) have been increasingly exploited and have become essential to modern society. More recently, nuclear energy has been mastered and used to produce large amounts of electricity.

1.1.8. Humans and Energy

A human needs energy to live. This energy is derived from food. Our basal metabolism requires about 2.7 kWh of energy per day. This corresponds to a power of 110 W. This is quite a small power considering the work done. With this small amount of energy all the organs are able to function, and it is also possible to carry out some limited activities. Interestingly, humans are actually more energy efficient than man-made devices.

> Humans and living species in general are very efficient energetic systems. As an illustration of that we can compare the amount of energy emitted from the sun divided by its mass (emitted energy per unit of mass) to the energy of the basal metabolism of a human divided by his/her mass. We find that the latter is more than 7000 times larger than the sun's energy density.

Pregnancy is a particularly energy-consuming human activity. It lasts 9 months, and it requires about 90 kWh of extra energy on the average. This corresponds to a daily extra energy of about 330 Wh or a little bit more than 10–15% of the average total energy needed. This explains why pregnant women need more food.

> A 1.5-ton car driving at 100 km/h (≈28 m/s) has a kinetic energy of about 580 kJ. Estimations show that a person hitting a nondeformable obstacle has a high probability of being killed if the car's kinetic energy is larger than about 700 J. This is a small amount and shows that if only a small part of the initial kinetic energy is transferred to the body of a passenger in a car accident, the passenger can die. Today's cars are designed in such a way that the materials they are made from deform and absorb a large part of the kinetic energy in a collision.

1.2. ALWAYS MORE!

The use of energy allows humans to be more efficient and to improve their way of life. Throughout history, humans have searched for better energy sources and better ways to harvest energy. A rough estimation of mankind's energy consumption through different periods of history is displayed in Figure 1.2.

The first energy source used by our remote ancestors (before humans mastered fire) was food. It was hard to find food, and it is estimated that the average

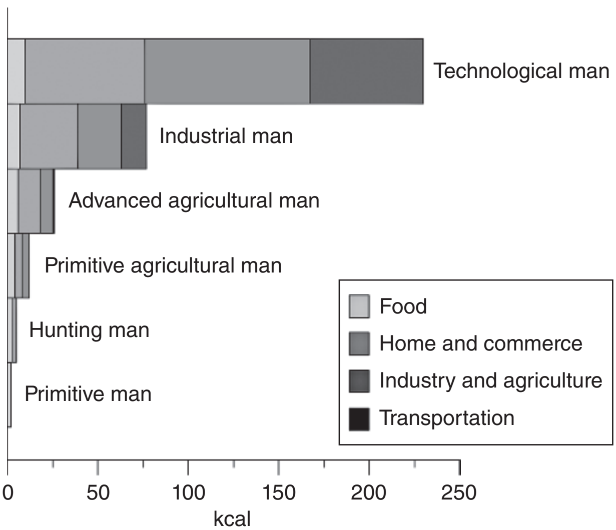

Figure 1.2. Estimated energy consumption per person per day over the ages. Data from E. Cook, *Scientific American*, 1971, and http://www.wou.edu/las/physci/GS361/electricity%20generation/HistoricalPerspectives.htm

food consumption provided an energy of 2 kcal per day. After fire was discovered and wood could be used for cooking and heating, a larger amount of energy (about 2.5 times more) was used. Agricultural activities again increased the energy needs, and the average total energy consumption nearly doubled. About 5000 years ago, primitive agricultural humans used animals to assist them in this work. By the end of the Middle Ages in Western Europe, advanced agricultural humans added the power of wind, water, and small amounts of coal. Transportation of goods was also developing and required more energy. Between 1400 and 1820, a French citizen's average wealth doubled primarily through the use of renewable resources. For comparison, a doubling of wealth in the second part of the twentieth century took only 25 years due to the more concentrated forms of energies. During the Industrial Revolution the energy consumption of industrial man rose by a factor of 3. The steam engine consumed large amounts of energy but also produced a lot of work. The advent of the use of the fossil fuels stored in the earth allowed a quick development of mankind's wealth.

Since the 1970s, technological man might be defined as an average US citizen: This person consumes more than 100 times as much energy as the primitive human. Electricity accounts for almost a quarter of this energy consumption and large quantities are used for transportation means, for industrial purposes, and for housing.

1.2.1. Why Do We Need More Energy?

It is estimated that the cumulative global population since the appearance of *Homo sapiens sapiens* has been about 80 billion people. Starting about a century ago the rate of increase of the population became very steep. Each day there is a net increase of about 200,000 people more on the planet (difference between babies who are born and people who die). These new inhabitants need energy to live, and this leads naturally to a continuous increase of primary energy consumption. The 1 billion wealthiest people in the world consume 66% of the food and 12 times more oil per capita than the people of underdeveloped countries.

Energy consumption increases over the ages for two main reasons. The first is that the population increases. Figure 1.3 shows the evolution of the global population over the past 2000 years. Figure 1.4 shows the dates for which successive population increases of one billion inhabitants have been reached.

> Before the French Revolution, more than 200 years ago, the energy consumption per capita in France was about 14 times less than today. Since the French population was about half of today's population, the total energy used in the country was about 28 times less at that time. The increase over more than two centuries is large but actually corresponds to an increase of only 1.3% per capita per year and 1.75% per year for the whole country. At the same time the life expectancy has increased from about 28 years at that time to 80 years today.

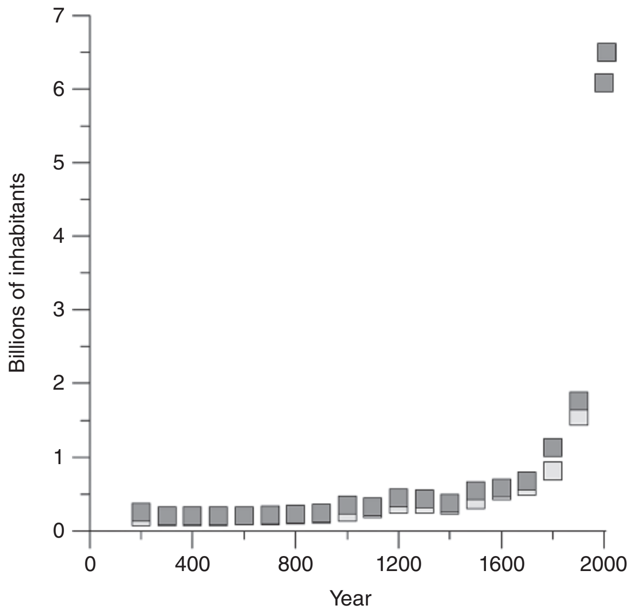

Figure 1.3. Evolution of global population. Because of uncertainties minimum and maximum estimates are indicated by open and closed symbols, respectively. Data from www.wikipedia.com

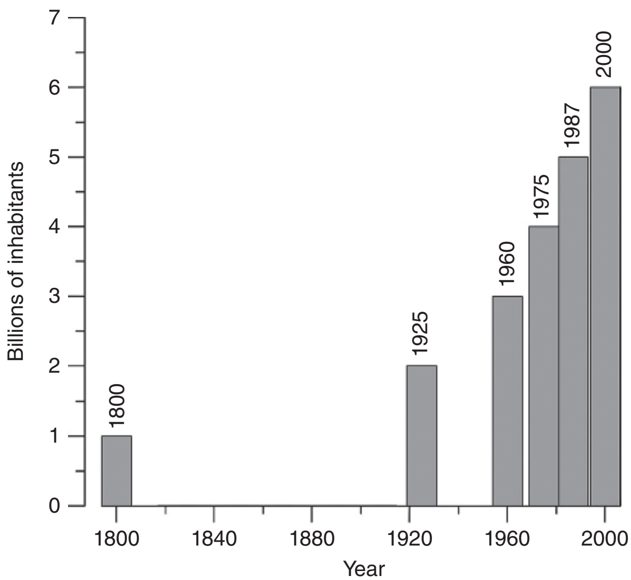

Figure 1.4. Dates at which successive population increases of one billion inhabitants have been reached. Data from http://villemin.gerard.free.fr/Economie/Populati.htm

The second reason why energy consumption increases is that the majority of people living on the earth live in countries that are still developing. There are currently 2.8 billion people living on less than \$2 per day and about 1 billion who live on less than \$1 per day. For a basis of comparison to energy costs, 1 kWh generated by an off-grid photovoltaic system (cells plus battery) costs around \$1.5. The only effective way for people in developing countries to increase their standard of living is to use more energy to develop their agricultural, industrial, and trading activities.

Life expectancy is strongly correlated with the amount of energy used. In Figure 1.5 the average lifetime expectancy is shown as a function of the energy consumption per capita. This is a mean curve that incorporates data from a number of different countries. The main message to be taken from the average trend shown in Figure 1.5 is that a minimal energy consumption is needed to reach a good life expectancy. People with little access to energy have short life expectancies. People having insufficient access to energy generally also have insufficient access to food, medicine, potable water, and so on. Data for most of the countries fall close to this curve, but there are a few exceptions. Some are shown in Figure 1.5. South Africa and Zambia have low life expectancies relative to the mean. This is primarily due to the AIDS epidemic. For Russia life expectancy is lowered by widespread alcoholism.

Figure 1.5 shows also that, above a certain threshold in energy consumption, about 3 toe per capita per year, the life expectancy levels off, indicating that in terms of lifetime expectancy there is no extra advantage of consuming more energy.

The increase in the world population and the increase of the standard of living in developing countries lead to an increase of global energy consumption that averages about 2% per year. Sustained at this level this would lead to a multiplication

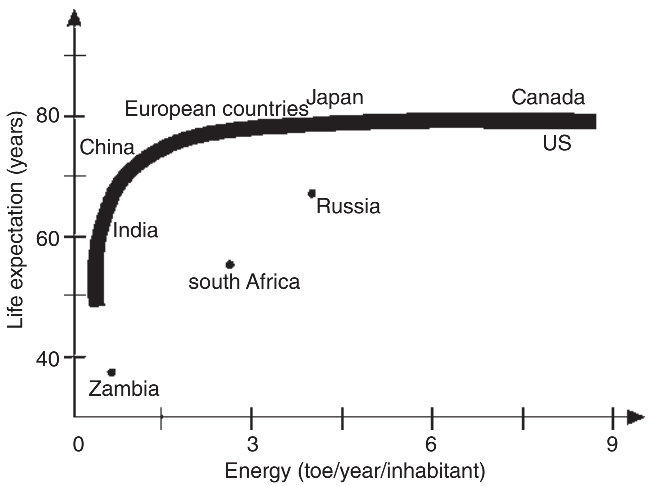

Figure 1.5. Curve of average trend of life expectancy versus primary energy consumption. Data from United Nations Development Program (2003) and B. Barré, *Atlas des energies*, Autrement, 2007.

of our energy consumption needs by 7 times between 2000 and 2100. This is clearly unsustainable as far as fossil resources are concerned. To keep improving our standard of living and allow developing countries to reach a similar standard of living, we have to develop alternative sources and learn how to use energy differently.

1.2.2. Energy Sources We Use

The different energy sources that we have described at the beginning are not equally used. Figure 1.6 shows the contributions of different energy sources to the world's total energy consumption in 2011. Only recently in the history of humankind have fossil fuels and nuclear energy, both concentrated sources of energy, been used extensively. Fossil fuels have been used for about two centuries, and nuclear energy has been used (to produce electricity) for only half a century. Their use allowed a rapid development of industrial and technological civilizations.

In 2011, energy derived from fossil fuels (crude oil, natural gas, and coal) provided more than 80% of the total energy used. Our modern world is extremely dependent upon fossil fuels. In the near future, it will probably become increasingly more difficult to meet our needs in this way.

In Figure 1.7, a sketch is shown depicting the contribution of various energy sources to primary energy consumption between the years 1800 and 2000. The "others" category includes renewable energies. These were heavily used in 1800. After the advent of the Industrial Revolution, the share attributable to renewable energies progressively decreased. Today, it accounts for just a little more than 12% of the total energy consumption. During the nineteenth century, coal progressively increased in importance, particularly at the beginning of the Industrial Revolution. The peak of coal's share was reached in the first quarter of the twentieth century. The relative contribution of coal decreased and then plateaued after midcentury. Today, there is a greatly renewed interest in coal because proven coal reserves are much larger than those of oil or gas. Around the mid-twentieth

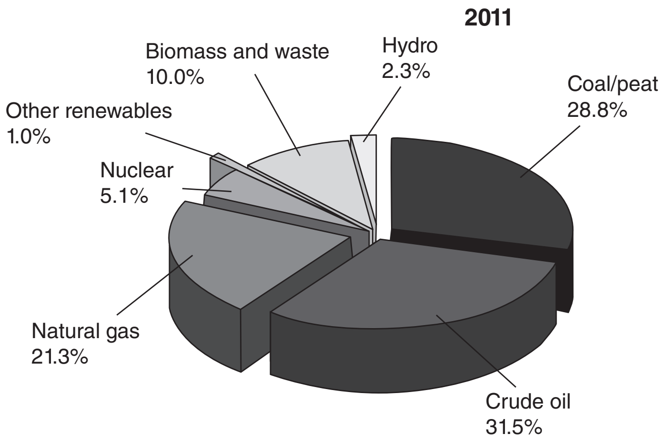

Figure 1.6. Distribution of world total primary energy supply in 2011. In 2011 the global primary energy supply was equal to 13.1 Gtoe. Data from www.iea.org

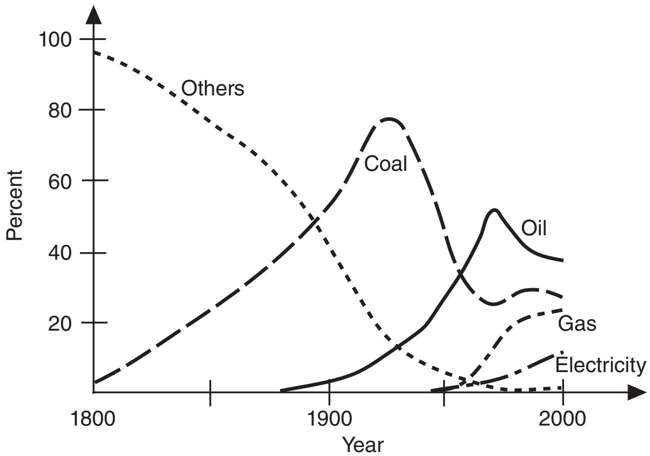

Figure 1.7. Percentage of different energy sources of total primary energy consumption, 1800–2000. Data from www.cea.fr

century, oil began to be a very important energy source because of its convenience. It is a liquid with a high energy density, particularly suitable for transportation applications. For a long time, natural gas was not used but flared. Fortunately, it was realized that it is a very good energy source, and it is now widely used due for the development of combined cycle gas turbines that provide a high efficiency for the production of electricity.

FINAL ENERGY CONSUMPTION

We identify "primary energy" as that available in an energy source before any transformation takes place. "Final energy" is the energy available to the consumer following transformation into gasoline, diesel fuel, electricity, etc. Typically during the transformation from primary energy to final energy there are inefficiencies that lead to energy losses in the system. At the global level the losses are substantial. In 2011, the total primary energy production was equal to 13.1 Gtoe, while the final energy supply was equal to only 8.9 Gtoe, about 2/3 of that initially available.

In Figure 1.8, we compare the distribution of final energy consumption as it existed globally and in the United States in 2011 and 1973. In the diagrams in Figure 1.8, "Other" includes residential, commercial, and public services, agriculture and forestry, fishing, and additional nonspecified sectors such as military fuel use, for example. "Nonenergy use" corresponds to resources that are used as raw materials and not consumed as a fuel or transformed to another source of energy. Nonenergy use of biomass (e.g.,

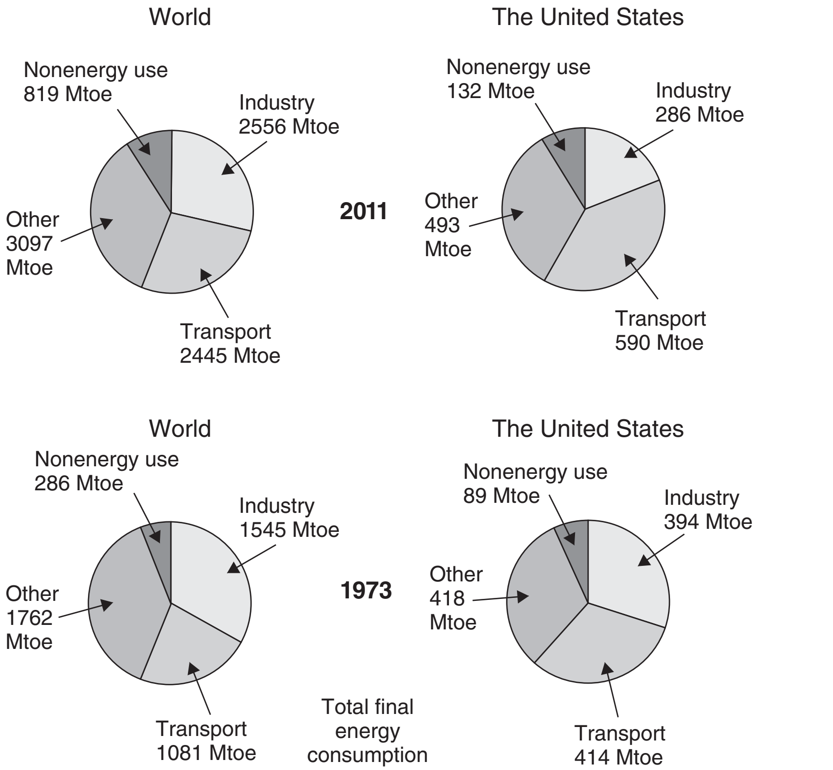

Figure 1.8. Final energy consumption in the world (left) and in the United States (right) during the years 2011 (top) and 1973 (bottom). Data are from www.iea.org

the amount of wood used in carpentry) is not registered in the energy sector.

Over a period of almost four decades (1973–2011), the amount of final energy consumption globally increased from 4.7 Gtoe to 8.9 Gtoe, almost 90%. In the United States, it increased from 1.3 Gtoe to 1.5 Gtoe, approximately 15%. During that same period the world's population increased 75%, from almost 4 billion in 1973 to 7 billion in 2011. In the United States the population grew 47%, from 212 million inhabitants in 1973 to 312 million in 2011. Thus, in the United States, the increase in final energy consumption was less than the increase in the population while it was greater than the population increase at the global level. In developed countries such as the United States there is a trend favoring energy efficiency, and some of the products that were initially made domestically are now manufactured in developing countries. The large global increase in final energy consumption in less developed countries is mainly due to the fact that these countries are now manufacturing a large number of commercial products for the rest of the world.

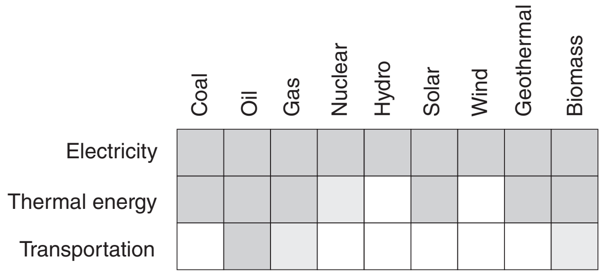

Figure 1.9. Possible uses of energy sources. Dark squares indicate that the application is possible and white ones that it is not possible. Light gray squares indicate limitations of use.

It is interesting to note that the amount of *renewable* energy consumed per inhabitant has remained almost constant over the past two centuries. It was around 0.2 toe in 1800 and is still the same amount today. However, the primary energy consumption per inhabitant was about 0.2 toe in 1800, but it is now a little bit larger than 1.7 toe.

The main uses of energy are to produce electricity, to produce heat (or cold), and for transportation. Not all sources of energy are well suited to meeting the needs for these applications, as is summarized in Figure 1.9.

Electricity is not an energy source but an energy vector. It is employed to transport energy from one point to another for use in many electric appliances. Electricity is being increasingly used in modern societies. The rate of growth of consumption for electricity is currently greater than the rate of growth of total energy consumption. Electricity can be produced by any source of energy. This possibility makes electricity a very convenient energy vector, and more and more systems are now powered by electricity.

All sources of energy cannot easily be employed to produce thermal energy directly. For example, it is not possible to produce heat efficiently with falling water. However, first producing electricity with a turbine and using this electricity in an electrical heater can generate heat. This is an indirect heat production method. Wind also cannot be used to produce heat directly. A nuclear reactor produces heat, a part of which is used to produce electricity. Each time 1 kWh of electricity is produced 2 kWh of heat is released into the environment. Heat produced by nuclear power can be used directly, but currently this is not done except in very specific cases.

Modern transportation is mostly based on oil as the energy source. While electric-powered vehicles exist, trains for example, they account for only a small amount of the energy used in transportation. In France, trains use about 7 TWh of electricity per year. This is a little less than the quantity of electricity produced by a single nuclear plant. For comparison, the power lost in the grid by the Joule effect is about 12 TWh per year in France.

Natural gas and biomass (through the use of biofuels) can be used for transportation but so far are used in limited amounts. Biofuels can provide a limited part of the demand but cannot completely replace oil. It is not possible, with the existing cultivatable lands, to produce enough biofuels to meet the demand. Natural gas–powered vehicles can also be used. They have the advantage of being

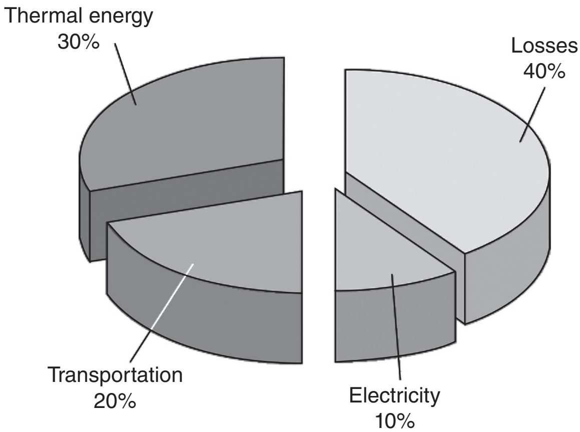

Figure 1.10. Rough distribution of primary energy among different applications. Data from B. Barré, *Atlas des energies*, Autrement, 2007.

less polluting than gasoline or diesel fuel. However, even compressed, a gas is less convenient than liquid fuels. Natural gas can meet a part of the energy demand for transportation but not all. Furthermore, in the longer term, natural gas suffers from the same problem of limited reserves as does crude oil.

In Figure 1.10, a rough estimate of the usage distribution of the world's primary energy is displayed. Thermal energy (heating or cooling buildings, domestic hot water production, etc.) accounts for the largest share. This means that the domain of thermal energy is the priority domain to be investigated in order to reduce our oil or gas energy consumption. It is also the domain where large effects in terms of reduction of pollution can be made. It is interesting to note that electricity accounts for only a small part of the initial primary energy consumption. The initial energy content of fuels used for transportation is about twice this amount. Just a small part of this primary energy is actually transferred to the wheels in the case of road transportation.

A large amount (about 40%) of primary energy is lost before reaching the end user. Much of this loss is due to physical laws that dictate maximum values for the efficiencies of thermodynamic processes. For example, the efficiency of a heat engine functioning with two heat sources at different temperatures is limited by the Carnot principle. On top of that, there are also losses due to the fact that there is usually a difference between an ideal system and a real operating device.

EXPLOITATION COSTS

Whether renewable or nonrenewable energy sources are employed, the main cost associated with their exploitation is associated with extraction, conversion, and delivery. Just as no one pays for the sun or the wind, no one has paid for the synthesis of oil, gas, or coal, or the creation of uranium isotopes used in reactors. What is expensive in terms of cost (and energy required) is to extract, transform, and deliver the energy from these natural energy sources. Finding oil, extracting, refining, and transporting it is expensive and requires sophisticated infrastructures. Building solar farms to harness solar energy or installing windmills to harness wind energy is also expensive.

Our ability to harness energy depends very much on the energy density of the primary source. Renewable energy sources are generally low energy density sources, and much effort is needed to concentrate the energy. Fossil fuels are about a million times more concentrated and are therefore very convenient for satisfying our present energy needs. Nuclear energy is even more concentrated, typically a million times more than fossil fuels. While the energy density is generally the most important parameter there is, of course, another consideration to be taken into account. For example, recovering crude oil from land-based wells is typically much easier than recovering it from large depths under the sea.

1.2.3. Security of Supply

Security of the energy supply is an essential concern for any country. In Figure 1.11, energy production and energy consumption (all energy sources are considered) are shown for different regions of the world. If the production is equal to the consumption, the region is energy sufficient. We see that there are regions that do not produce enough energy and others that produce too much energy for their own needs. North America, Asia, and Europe do not produce enough energy, and they must import energy. The figure for Europe includes the former USSR and in particular Russia, which has large energy resources, including a lot of natural gas.

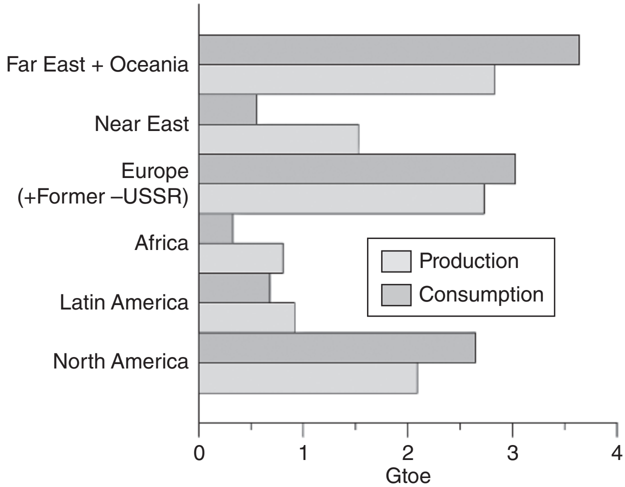

Figure 1.11. Production and consumption of primary energy in different regions of the world, 2006. Data from Pétrole, *Elements de statistiques*, Comité professionnel du pétrole, 2006.

This brings Europe's production and consumption close to each other but does not reflect the real political situation. Indeed, the remaining part of Europe imports a lot of energy from Russia and elsewhere.

Table 1.4 shows the level of the European Union's dependence on external sources for its oil and gas. It is large and expected to increase in the next decade.

Figure 1.12 shows the distribution of the different energy sources used to meet primary energy consumption in the United States. Oil supplied 40.5% of the primary energy. The US oil production was not capable of meeting the whole demand. Therefore, it was necessary to import oil. The origin of the oil imports is shown in Figure 1.13. Dependence on Middle East oil is not as large as most might think. However, in the future the share derived from that source is expected to increase because most of the petroleum reserves are in this area of the world.

TABLE 1.4. Level of Dependence of European Union on External Energy Sources of Oil and Gas

	Level of Dependence (%)	
	2004	2020 (Forecast)
Oil	80	90
Gas	54	70

Source: Data from J. P Favennec, *Géopolitique de l'énergie*, Technip, 2007.

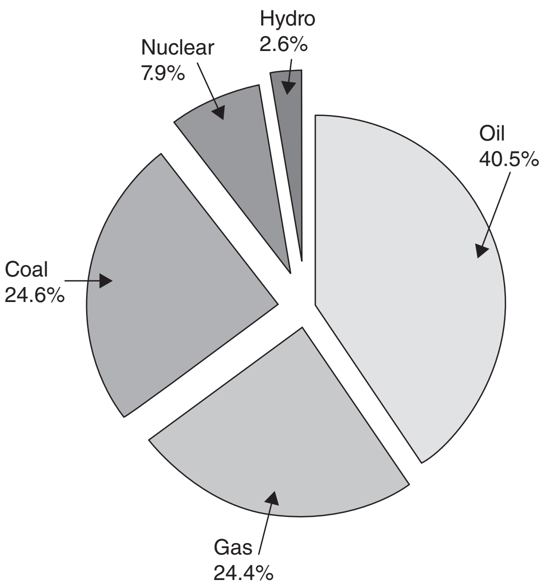

Figure 1.12. Distribution of different energy sources for primary energy consumption in the United States, 2005. Data from J. P. Favennec, *Géopolitique de l'énergie*, Technip, 2007.

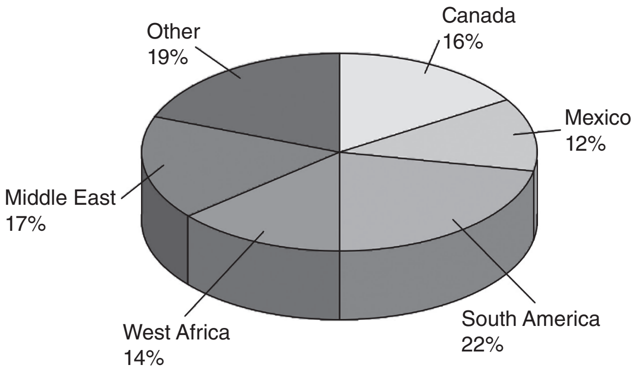

Figure 1.13. Origin of different oil imports done by the United States, 2005. Data from J. P. Favennec, *Géopolitique de l'énergie*, Technip, 2007.

TABLE 1.5. Daily Production in Selected Middle East Countries, 2007

Country	Production (Mbbl/day)
Saudi Arabia	10.9
Iran	4.4
Iraq	2.1
Kuwait	2.6
United Arab Emirates	2.9
Qatar	1.2
Oman	0.7
Yemen	0.3

Source: Data from BP, *Statistical review of world energy*, www.bp.com, 2008.

In Table 1.5 the daily production of oil in barrels (bbl) is shown for different countries of the Middle East in 2007. Saudi Arabia dominated oil production in this area, producing more than 10 Mbbl/day.

The regions to which crude oil produced in the Middle East is exported are shown in Figure 1.14. A large part is exported to Asia.

Because oil and gas are such important energy sources, a lot of effort is devoted to finding new sources. The number of oil and gas wells drilled between 1998 and 2006 is shown in Figure 1.15. The number almost doubled in that period, reflecting some urgency in the effort to discover new resources.

In Figure 1.16 are shown percentages of the different energy sources employed in Russia in 2005. Natural gas was the dominant source of energy because of the large resources of natural gas in that country. The world's largest known reserves of natural gas are found in the former USSR.

Natural gas is also exported from Russia in large quantities. The regions to which it is exported are shown in Figure 1.17 as percentages of total exports. We see, as noted earlier, that the European Union is very strongly dependent upon the Russian gas.

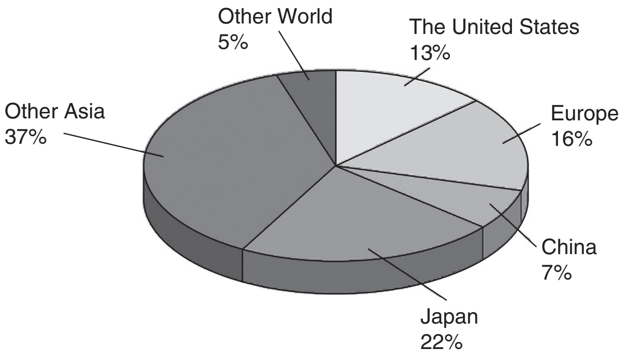

Figure 1.14. Regions to which crude oil produced in the Middle East is exported. Data from J. P. Favennec, *Géopolitique de l'énergie*, Technip, 2007.

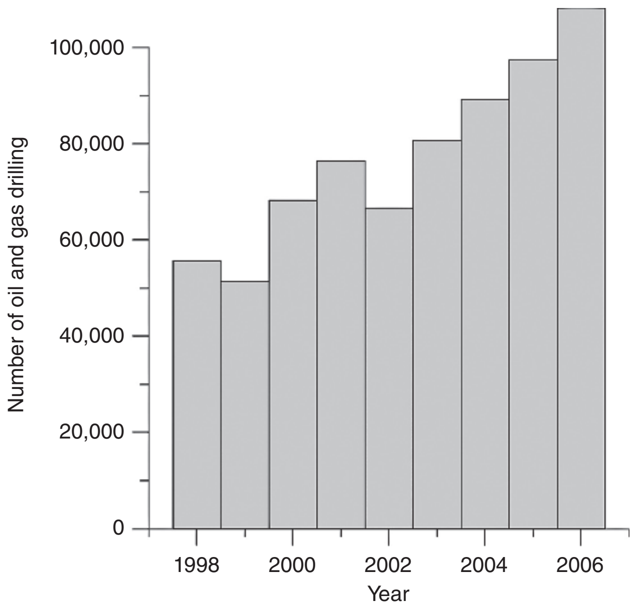

Figure 1.15. Global number of oil and gas wells drilled between 1998 and 2006. Data from Pétrole, *Elements de statistiques*, Comité professionnel du pétrole, 2006.

This discussion applies to conventional oil and natural gas. Large-scale harvesting of unconventional fossil fuel resources, shale gas, or shale oil, for example, is now occurring. Chapter 3 is devoted to these new resources, which are changing the world energy geopolitical landscape. For example, by exploiting such newly accessible resources, the United States may become the leading oil producer in the world by the end of the decade.

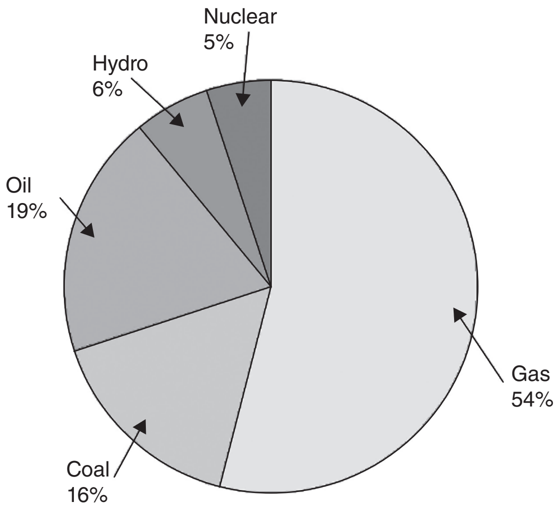

Figure 1.16. Percentages of different energy sources for primary energy consumption in Russia, 2005. Data from J. P. Favennec, *Géopolitique de l'énergie*, Technip, 2007.

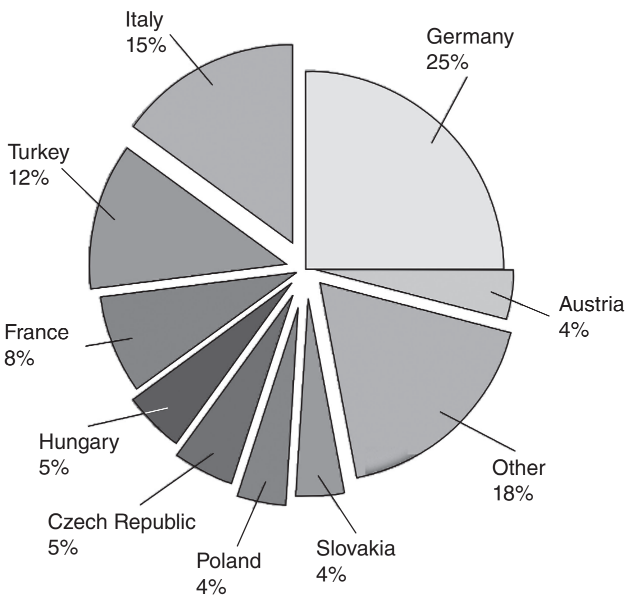

Figure 1.17. Regions to which Russian natural gas is exported, and percentages with respect to total export, 2005. Data from J. P. Favennec, *Géopolitique de l'énergie*, Technip, 2007.

In Figure 1.18, the evolution of the different sources used to produce electricity in France is shown starting from 1950. There has been a strong increase in the demand for electricity since that time, and new means for the production of electricity were needed to meet that increasing demand. Until the 1970s, electricity

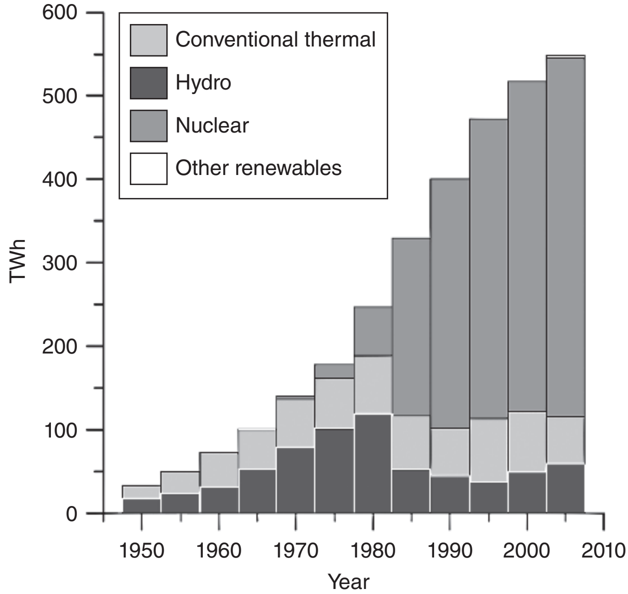

Figure 1.18. French inland electricity production, 1950–2010. The conventional thermal, hydro, nuclear, and other renewables contributions are shown on a gray scale. Data from *Energy Handbook*, CEA, 2006.

was mostly produced by hydro and fossil fuel plants. In order to ensure safety of its energy supply, France strongly developed nuclear power after the first oil shock. After the decision was taken to build the nuclear plants, it took a long time to construct them. This explains why a noticeable amount of electricity produced by nuclear power appeared only in the 1980s. The production of electricity by nuclear power has increased the level of energy independence of the country (≈50%). At present 90% of France's electricity is produced without CO_2 emissions (nuclear plus hydro).

ALL kWh ARE NOT EQUAL

Many different energy sources can be used to produce electricity and generate kWh. However, all of these kWh are not equivalent from the consumer point of view. Even without considering impact on the environment or taking into account the production cost per kWh, the different energy sources are not equally convenient. For example, fossil fuels (oil, natural gas, and coal) can be used to produce electricity continuously. This is also the case for nuclear fuels. While some renewable energy sources are able to produce electricity on demand, as in the case of hydropower provided there is water available, this is not generally the case. Wind-produced electricity is generated only when there is wind, and solar-produced electricity is generated only when the sun is shining. Furthermore, the power output strongly depends on the wind speed or on the intensity of sunlight. In these cases, the production is not reliable. In order to compensate for this drawback, storage capabilities or alternative generation capabilities (e.g., a gas-fired plant) are required to produce electricity when there is not enough wind, or enough hours of sunlight. In addition, a smart grid may be required to manage the intermittence of these energy sources. Therefore, a kWh produced continuously is not the same as that produced intermittently and has not the same value. This is summarized in Figure 1.19.

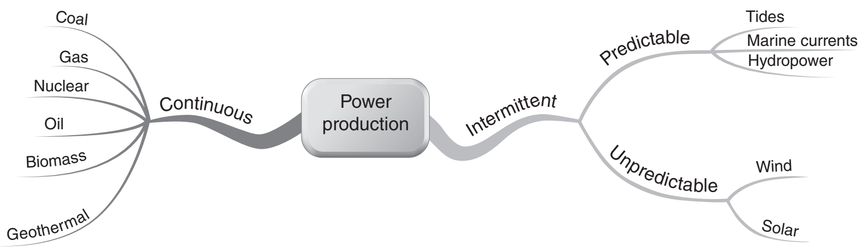

Figure 1.19. Electricity can be produced using different sources, but the output is not always of the same reliability. In some cases power can be obtained on demand, while in other cases power is delivered only when the energy source is available.

1.2.4. Environmental Concerns

Progress in the energy domain has always been necessary to meet expanding demand. The main problems associated with keeping pace with the demand are that global population increases and energy consumption per capita also increases.

Our use of energy has an impact on our environment. Since a huge amount of energy is consumed in the world, the impact can be large. This impact can be on a local or a global scale. Nitrogen oxides emitted by the exhaust pipe of a car pollute at the local scale, while the CO_2 emitted has an effect at the global scale. Pollution is not a new phenomenon. Chronicled already around the fifth century by Lao Tsu in China who described the impact of human activities on the environment, pollution already existed much earlier. Towns and cities were especially polluted. The energy supply in the Middle Ages was dominated by wood. This resource began to become increasingly scarce, and the replacement of wood by coal allowed the Industrial Revolution. There were less people during the nineteenth century compared to today, but pollution in towns was greater because coal was widely used and no special care was taken against pollution. For a long time coal was not a welcome energy source. For example, in England, Edward I published strong regulations restricting the use of coal in London close to the royal palace: "whosoever shall be found guilty of burning coal shall suffer the loss of his head." Later the use of coal was regulated on a larger scale by Richard II. The famous London smog was already described in a publication around 1650. As late as 1952, between the December 5 and 9, about 4000 people died in London during the "great smog."

The age of the automobile ushered in an era of significant pollution in many other urban areas. Due to regulation and technological advances, emissions from cars have been significantly reduced. Except for CO_2 a reduction factor of 100 is often achieved for pollutants coming out of the exhaust pipes of vehicles. Environmental concerns are now being taken more seriously by society, and practices that were common a few decades ago are no longer as accepted today. The environmental impact of different energy sources will be discussed in the individual chapters dealing with those sources.