Units of energy measurement and conversion factors

Units of energy measurement

1 calorie	4.186 joules
1 kWh	3.6×10^6 joules
1 thermie	4.186×10^6 joules
1 BTU (British Thermal Unit)	1.055×10^3 joules
1 quad	10^{15} BTU
1 barrel of oil	159 litres
1 US gallon	3.785 litres

Conversion factors

1 tonne of oil equivalent (LHV)	42×10^9 joules
1 tonne of coal equivalent (LHV)	29.3×10^9 joules
1000 m^3 natural gas (LHV)	36×10^9 joules
1 tonne liquid natural gas	46×10^9 joules
1000 kWh (primary)	0.0857 TOE (hydro)
1000 kWh (primary)	0.26 TOE (nuclear)
1 tonne natural uranium (PWR)	4.2×10^{14} joules

Chapter 1
Basic concepts

Energy is necessary for all life and all economic activity. Like food and water, energy is indispensable. It has played a fundamental role in the development of civilisations. It has been the cause of war between peoples who have sought throughout history to control access to energy resources. During the twentieth century, easy access to abundant, cheap and concentrated sources of energy enabled faster economic development. The discovery of electricity, a highly convenient carrier of energy, revolutionised the use of energy, and it is almost impossible to imagine a modern house without electricity. However, despite this progress, a considerable proportion of humankind still cannot satisfy its energy needs. Since earliest times, human's energy needs have continually increased. Today we live in a world where we are always needing more, although it is clear that we are reaching the limits of this headlong rush for growth. We need to resolve the thorny problem of how to make further progress without consuming more energy.

Although everyone has a basic idea of what energy is, in reality it is not a notion which is that simple to define. The concept has many faces, and the aspect which interests us here is a particular one that we will now examine more closely.

1.1 What is energy?

Scientists maintain that the fundamental processes (physical phenomena, chemical reactions, biological processes, etc.) that govern our macroscopic world (of objects and living creatures) are ruled by a law in which a physical quantity, which we call *energy*, is always conserved in an isolated system. This is a fundamental law and is associated with the fact that the laws of physics do not change with time. In simple terms, this property translates into the fact that the results of an experiment do not depend on the time it was carried out provided that it was done under exactly the same conditions.[1]

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[1] Space is also homogenous and isotropic, which leads, respectively, to two laws of conservation: the law of impulsion and the law of kinetic momentum. The homogeneity (isotropy) of space means that an experiment yields the same results if one makes a translation (or a rotation) of the experimental system.

If energy is a physical quantity perfectly defined for the physicist, its dictionary definition is much less clear. But what interests us here pragmatically is that a system or a body possesses energy if it can produce *work* or *heat*.

According to this definition, petrol contains energy since we can use it to propel a vehicle. But this same petrol, when burnt, can provide heat.

At the microscopic level, energy can be seen to exist in either an *organised* or *disorganised* form. In the first case we call it *work*, in the second *heat*. Heat represents the lowest form of energy, because it is distributed over all the degrees of freedom of the system in question, and these are very numerous.[2]

The particularity of energy is to exist in different forms: mechanical, heat, nuclear, etc., and it is very often necessary to convert one form of energy into another. This is done with a certain yield and also loss. When energy passes from a disorganised form (heat) to an organised form (work) the efficiency is rarely good. It is through these transformations from one form to another that humans recover a part of the energy that is exploited for their own needs. It is therefore not the energy contained in a body that is interesting, but that which is acquired through its transformation.

All forms of energy are therefore not of the same quality and cannot be used efficiently to produce work. Thus, a heat source of 300 °C is much more efficient in producing work than a heat source of 50 °C.

The use of energy enables humans to improve their welfare by helping them to feed themselves, keep warm and so on. *Primary energies* are distinguished from *final energies*. *Primary energy* has not undergone any conversion between production and consumption.[3] This is the case with oil, coal, natural gas, hydropower, wood, solar and wind energy. The *final energy* delivered to consumers can be used to meet energy or non-energy needs.

This distinction between primary and secondary energy can have consequences for the evaluation and comparison of different energy sources as can be seen in Figure 1.1. Thus nuclear energy and hydropower produce, on a global scale, much the same quantity of electricity for the consumer. These two sources have the same output, but statistics show us that nuclear energy actually makes three times more primary energy than hydropower (Figure 1.1). The reason is that hydropower is a primary energy and the electricity is produced with an efficiency close to 100%. The electricity produced by nuclear power, which is the energy liberated from uranium fission, on the other hand is not accounted for as a primary energy. Since the efficiency of today's power-generating stations is around 33%, nuclear energy creates three times more primary energy than hydropower, though the energy used by the consumer is the same.

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[2] In a small glass of water weighing 20 g, the number of degrees of liberty of the water molecules is a multiple of the Avogadro constant ($N = 6.02 \times 10^{23}$). There are therefore more than 10^{24}, that is more than a million billion billion molecules. The heat contained in this water is spread between all these degrees of freedom, and therefore each one possesses very little.

[3] Crude oil is a primary energy, whereas the petrol or diesel obtained by refining are secondary energies. Electricity produced by hydropower or photovoltaic panels is primary, whereas energy of nuclear origin is secondary. Charcoal (secondary energy) is produced from wood (primary energy).

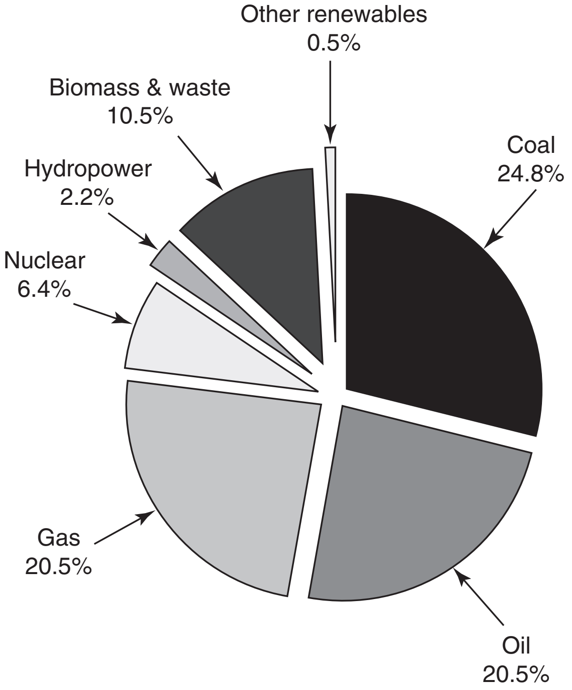

Figure 1.1 World consumption of primary energy in 2004. Totals do not exactly equal 100% because of rounding errors. [Source: IEA World Energy Outlook 2006]

1.1.1 Units

The internationally accepted unit of energy is the *joule* (J). For macroscopic transformations this unit is too small so one uses kilojoules (kJ) or megajoules (MJ): $1\ \text{kJ} = 1000\ \text{J}$ and $1\ \text{MJ} = 10^6\ \text{J}$. Table 1.1 lists the twenty SI prefixes used to form decimal multiples and submultiples of units.

For energy released at the atomic, molecular or nuclear level, the unit used is the *electronvolt* (eV) and its multiples. Its definition is: $1\ \text{eV} = 1.6 \times 10^{-19}\ \text{J}$. Energy released in elementary chemical reactions is of the order of a few eV,

Table 1.1 SI prefixes

Prefix	**× by**	**Symbol**	**Prefix**	**× by**	**Symbol**
yocto	10^{-24}	y	yotta	10^{24}	Y
zepto	10^{-21}	z	zetta	10^{21}	Z
atto	10^{-18}	a	exa	10^{18}	E
femto	10^{-15}	f	pecta	10^{15}	P
pico	10^{-12}	p	tera	10^{12}	T
nano	10^{-9}	n	giga	10^{9}	G
micro	10^{-6}	μ	mega	10^{6}	M
milli	10^{-3}	m	kilo	10^{3}	k
centi	10^{-2}	c	hecto	10^{2}	h
deci	10^{-1}	d	deca	10^{1}	da

while that released in nuclear reactions is more than a MeV – more than a million times greater. These elementary values may seem small, but there are a large number of elementary reactions in the processes carried out at that scale. For instance, 16 g of methane (1 mol), the basic ingredient of natural gas, contains $N = 6.02 \times 10^{23}$ molecules.

Power is a quantity of energy by unit of time. The basic unit is the *watt* (1 W = 1 J/s). In the energy field, the megawatt (1 MW = 10^6 W), gigawatt (1 GW = 10^9 W) and terawatt (1 TW = 10^{12} W) are often used.[4]

In the field of electricity, the usual energy unit is the watt-hour (Wh) and its multiples. The watt-hour represents an energy of 1 J/s during 1 h. Thus, 1 Wh = 3600 J and 1 kWh = 3.6×10^6 J. The kWh which is a measure of energy must not be confused with the kW which is a unit of power. Also used are the MWh (1 MWh = 10^6 Wh), the GWh (1 GWh = 10^9 Wh) and the TWh (1 TWh = 10^{12} Wh).

1.1.2 Equivalences

To compare different sources of energy it is usual to use as a yardstick the energy provided by crude oil. The conventional unit is the tonne of oil equivalent (TOE), the value of which is fixed at 10^{10} cal (1 cal = 4.18 J) $\approx$ 42 GJ ($\approx$ 11,700 kWh) [3]. In fact the equivalence 42 GJ $\simeq$ 11,700 kWh corresponds to a direct conversion between the joule and the kWh, with an efficiency of 100%. In practice, for the conversions made the efficiency of the generating station is factored in, which leads to 1 MWh = 0.26 TOE when electricity is produced by a nuclear power station (33% efficiency), 1 MWh = 0.86 TOE for a geothermal power station (10% efficiency) and 1 MWh = 0.086 TOE for electricity produced by a thermal power station or the photovoltaic process, etc. (100% efficiency). This explains why 1000 kWh of electricity represents 0.0857 TOE when produced by hydropower and 0.26 TOE when produced by nuclear reactors, and hence the factor of 3 as mentioned earlier.

When dealing with combustion, one may refer to lower heating value (LHV) or higher heating value (HHV). HHV includes the latent heat of the water vapour produced during combustion whereas the LHV excludes it. As this latent heat is not usually recovered in current processes, LHV is usually used and the TOE is defined according to this convention. The calorific value of crude oil varies slightly between one source and another; it also differs for the various refined petroleum products (1 tonne of petrol = 1.048 TOE, 1 tonne of liquefied petroleum gas (LPG) = 1.095 TOE, 1 tonne of heavy fuel oil = 0.952 TOE [3]).

Coal has a lower calorific value than oil, typically between 0.6 and 0.75 TOE depending on its quality (steam coal, coke, anthracite, etc.). Sometimes the measure of TCE (tonne of coal equivalent) is conventionally set at

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[4] The *horse power* (1 HP = 736 W) is an old unit introduced by Watt and now out of use. It was based on the work that a vigorous horse could carry out, since the power of one horse power is roughly equivalent to the work of three normal horses [2]. At the end of the nineteenth century, 16,500 horses were needed to work the 38 tramlines of Paris.

1 TCE = 0.697 TOE [3]. Natural gas has a calorific value slightly higher than oil, 1 tonne of liquefied natural gas (LNG) being equivalent to 1.096 TOE (1000 m^3 is equivalent to 0.857 TOE) but 1000 m^3 of natural gas equivalent to 0.857 TOE.

1.2 Energy and development

Energy has always played a major role in human development. Energy consumption increased rapidly following the industrial revolution, particularly during the twentieth century, but this is a much faster process than that which our ancestors experienced in the past. For thousands of years humans were happy with a power of a few hundred watts, at first with their own physical strength then exploiting the strength of their domestic animals. Let us briefly recall the first stages [4].

Human's first energy consumption was naturally food. It enabled them to survive and reproduce. This basic need was extended by other forms of energy that played an increasingly important role in the development of humankind.

Around 500,000 years ago, humans discovered fire and learned to control it. This provided them with light to see at night and scare off wild animals, heat to protect against the cold and to cook their food. About 7000 years ago, humankind invented charcoal that enabled them to make hotter and more efficient fires, and so developed new techniques such as pottery, lead and copper metallurgy, and the manufacture of plaster and lime. Then, about 3000 years ago, they discovered how to smelt and work iron.

As long as humans were hunter-gatherers, their own strength, combined with their intelligence and skills, and fire, were sufficient. But once they started to practise settled agriculture they needed new sources of energy to work the land and mill grain more efficiently. They found this energy in the strength of domestic animals and slaves. The need for slave labour explains the expansion of the Roman Empire, for example. Later, renewable forms of energy largely replaced slaves.

Another form of energy our ancestors needed was for transportation, which is at the heart of our civilisations today. Early means of transport were the backs of human beings and animals. Then sea transport was made possible by using sails to harness wind energy. Coal combustion powered steam engines and petroleum brought the motor car.

While in the developed countries, energy demand, after growing massively, is stabilising and is likely to diminish, thanks to improved *energy efficiency*,[5] in the developing countries it is still growing strongly, as these countries attempt to attain the economic level of the rich countries.

Ten thousand years before the birth of Christ, the world population is believed to have been 5 million, rising to 250 million in 1 AD. The first billion was reached in 1820, and it took 105 years for the population to double to

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[5] Energy efficiency increases as the same or more work is done with less energy.

2 billion in 1925. Population then increased more rapidly to 3 billion in 1961 and 4 billion in 1976. Six billion was reached in 1999, and in 2009 the population has already reached 6.8 billion. Demographers forecast that, barring catastrophe, world population will reach 8 billion by 2020–25. Projections for the end of the twenty-first century are more uncertain, and population is likely to be smaller than was projected 10 years ago. The most likely scenario is in the range 9–10 billion.[6] Population growth inevitably results in increased demand for energy.

In 2004, world consumption of electricity was 17,400 TWh for a population of 6.4 billion. Average annual consumption is 2700 kWh/person, but this figure does not reflect the real situation in which more than 4 billion people consume less than this value. The domestic electricity consumption of France in 2004 was 477 TWh, of which 32 TWh were lost [5], representing for France's population of some 61 million, an average annual consumption of around 7800 kWh/person.

Life expectancy seems partly correlated to electrical energy consumption because of its impact on countries' standard of living. Life expectancy falls sharply (sometimes as low as 36.5 years) when annual energy consumed is below 1600 kWh/person. At the end of the twentieth century, 3.5 billion people consumed less than 875 kWh/person/year, 2.2 billion of those less than 440 kWh/person, and 1 billion less than 260 kWh/person [6]. The rate of infant mortality also increases sharply when total energy consumption is below $\sim$4400 kWh/person/year [6].

Let us consider some further examples showing the consequences for life expectancy of inequalities in access to energy. Eighty per cent of world energy is consumed by 20% of world population and these people have a life expectancy over 75 years. Sixty per cent consume 19% of energy and their life expectancy is over 50 years. The remaining 20% of world population consume 1% of global energy and their life expectancy is below 40 years.

In 1796, with a population of 28 million, France consumed an average of 0.3 TOE/person/year. Two hundred years later in 1996, consumption had risen to 4.15 TOE/person/year. This was an increase by a factor of 14 per person and 28 for France, because the French population doubled over the period. This corresponds to an average growth in consumption of 1.3% per year, and for France of 1.75% per year. Currently, the global growth in energy consumption is forecast to be 2–2.5% per year. In 200 years, life expectancy in France increased from 27.5 years for men in 1780–89 to 73.5 years in 1994, and for women from 28.1 to 81.8. In 2006, average French life expectancy was 80 years.

The development of the GDP (gross domestic product) per person gives an idea of the prosperity of individuals. In France, between 1400 and 1820, it

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[6] A world population of 8 billion in 2020 represents an average growth of 1.4% from 2000. If this growth rate was applied over 1000 years, for example, it would result in a total population of 6.5 million billion, which of course is completely unrealistic. An annual growth rate of only 0.2% would result in a total of 50 billion in 1000 years. Conversely, a rate of decline of 0.2% would result in a decline in world population from 6 billion to 810 million in 1000 years.

increased by 0.2% per year that is equivalent to a multiplication of prosperity, over 420 years, of 2.3 times. Since 1950, the increase has been 2.8% per year, a fourfold multiplication of prosperity in 50 years.

Energy should not be wasted, because while it is cheap today,[7] it is likely that this will change in the future. We must prepare for tomorrow by developing every possible source of energy, taking into account the economic, political, security of supply and environmental aspects. In particular, we must apply the true costs of energy that include what economists call the externalities (pollution, greenhouse effect, decommissioning, etc.). These are generally not taken into account, except in rare cases like nuclear energy.

1.3 The Sun

The Sun is a spherical star which is our source of life, for it provides most of the energy that we use today. In fact, apart from geothermal and nuclear, all energy comes from the Sun.

The Sun has a radius of 696,000 km and a mass of the order of 1.99×10^{30} kg. Its surface temperature is 5780 K.[8] According to the Standard Solar Model, accepted by the whole scientific community, the Sun's temperature increases considerably beneath the surface, and reaches 15.6 million degrees in the centre. The Sun consists (by mass) of 71% of hydrogen,[9] 27% of helium and 2% of heavy elements such as carbon, oxygen and iron. The density and pressure at the centre are, respectively, 148,000 kg/m^3 and 2.29×10^{11} times atmospheric pressure.

The Sun was formed 4.55 billion years ago by the gravitational contraction of a cloud of hydrogen, helium and traces of other elements [7]. This process was rapid until the atoms of the cloud were ionised. The energy could no longer escape from this cloud and it slowly contracted. Half of the gravitational energy liberated was converted into radiation and the other half served to heat the cloud. The contraction continued and the cloud heated up. When the temperature was close to 1 million Kelvin, thermonuclear fusion reactions between hydrogen and the light elements such as deuterium, lithium, beryllium and boron began. As the light elements were present in small quantities, the liberation of energy was limited, but was enough to form a gas of very high temperature and set off the fusion reactions between the large numbers of hydrogen atoms, or, to be more precise, the protons.

Most of the thermonuclear reactions took place in the centre of the Sun in a volume corresponding to a sphere whose radius was only about 20% of the Sun's [8]. They provided the Sun with energy and led to the formation of nuclei of helium, ^{4}He, which is a particularly stable element. In the Sun, hydrogen is

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[7] A 'barrel' of some mineral waters costs around \$140, or twice as much as crude oil at \$70 a barrel.

[8] This temperature means that a large part of the Sun's radiation is in the visible spectrum. The energy radiated by the Sun is around 4×10^{26} W.

[9] Or more than 90% in terms of the number of atoms.

consumed in fusion reactions, the first stage of which is the interaction between two protons.[10] Altogether four protons are needed to generate one nucleus of helium. These fusion reactions are classified into three families. The first[11] occurs in 85% of cases and liberates 26.2 MeV. The second family (15% of cases) liberates 25.7 MeV and the third (in only 0.2% of cases) liberates 19.1 MeV.

The average energy liberated by a proton in a fusion reaction is 15 MeV. The first reaction of each family corresponds to a reaction between two protons. The probability that the two will react is very small; among the 3×10^{31} m^{-3} protons present, only 5×10^{13} m^{-3}/s lead to fusion. The energy liberated is 120 W/m^3, ten times less than the energy the human body needs to survive ($\simeq 1400$ W/m^3) [7].

During fusion, it is the first reaction between two protons which is the slowest and which governs the process. Some 5 billion years are needed for one proton (^1H) to fuse with another proton [7] to form a deuteron (^2H). But only about one second is needed for the deuteron formed during this reaction to react with a proton to create a ^3He. Around 300,000 years are needed for two ^3He to meet and form a nucleus of helium, ^4He. This low probability of reaction means that the density of the energy emitted in space by the Sun is very weak: 200 nW/g, or 7000 times less than the energy released by a human being's metabolism ($\simeq 1.4$ mW/g).[12]

For the Sun, hydrogen is not a renewable energy. This fuel will gradually run out, and in about 5 billion years, the Sun will become a 'red giant'. The central part of the core will contract and heat up until the temperature and density of matter reaches a point at which thermonuclear fusion of the helium is triggered. At the same time, the external part of the Sun will expand to form a 'red giant'. The Earth will be destroyed during this expansion [9].

1.4 Energy consumption

The various sources of primary energy that we can use are fossil and mineral resources (coal, oil, gas, uranium) and renewable energies (hydro, solar, wind, biomass, geothermal). The problem with many of these sources is their availability and cost.

Until 200 years ago, humans only used renewable energies: wood for heating and cooking, animal traction for transport, water and wind power for

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[10] When fusion reactions between neutrinos (ν_e) and photons (γ) are created, the probability of a neutron formed in the centre of the Sun escaping from the Sun without interaction is 10^{-9}, which means that only a single neutrino out of a billion interacts before escaping. It is much more difficult on the other hand for a photon to escape from the Sun on account of the successive interactions which it undergoes. A photon created within the Sun will take some 50,000 years to escape from it.

[11] $^1H + {}^1H \rightarrow {}^2H + e^+ + \nu_e$
$^1H + {}^2H \rightarrow {}^3He + \gamma$
$^3He + {}^3He \rightarrow {}^4He + 2\,{}^1H$

[12] The metabolism of a child, which needs more energy than adult metabolism, is around 3 mW/g. The metabolism of a bacterium can reach 100 W/g [1].

mechanical energy. During the nineteenth century, coal mining led to the development of steam engines. In the twentieth century, oil, gas and nuclear energy were exploited.

Total energy consumption worldwide (commercial and non-commercial) in 2004 was 11.2 GTOE. Fossil fuels (oil, coal, gas) covered more than 80% of requirements (see Table 1.2). The predominance of fossil fuels can also be seen in Figure 1.1.

The growth of primary energy consumption in France between 1960 and 2000 is shown in Figure 1.2. During this period, consumption tripled, representing an annual growth 2.8%. In 2005, consumption reached 276.3 MTOE. However, huge losses take place between the primary and the final energy used by the consumer. Thus, in France, the final energy consumed in 2005 was 160.6 MTOE,

Table 1.2 Consumption of primary commercial energy worldwide in 2004

Energy	**GTOE**	**%**
Oil	3.940	35.2
Gas	2.302	20.5
Coal	2.773	24.8
Nuclear	0.714	6.4
Hydro	0.242	2.2
Biomass & waste	1.176	10.5
Other renewables	0.057	0.5
Total	**11.204**	**100**

Totals do not exactly equal 100% because of rounding errors (Source: IEA World Energy Outlook 2006).

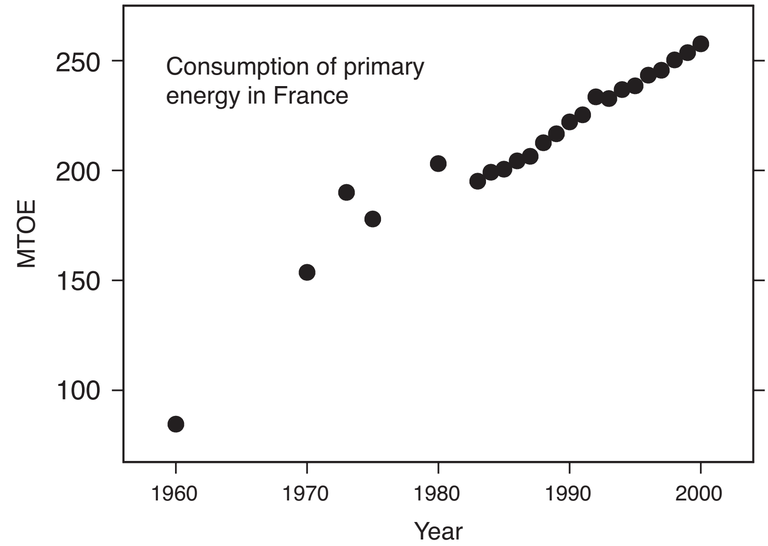

Figure 1.2 Development of primary energy consumption in France [5]

only 68% of primary energy. The distribution of energy consumption in France in 2008 across different energy sources is shown in Table 1.3 [11].

Table 1.3 Consumption of primary energy in France in 2008

Energy source	MTOE	%
Coal	12	4.4
Oil	89	32.5
Gas	41	15.0
Electricity (nuclear and renewables)	117	42.7
Thermal renewable energy	15	5.5
Total	**274**	**100**

Totals do not exactly equal 100% because of rounding errors (Source: DGEMP).

Electricity is used the most widely. Figure 1.3 shows the development of domestic electricity consumption in France up to 2000 [5]. It increased by a factor of 6.125 between 1960 and 2000, an annual growth rate of 4.64%. Between 1970 and 2000, consumption rose from 140 to 441 TWh (482 TWh in 2005). During the 1970s, it was therefore necessary to find new means of generating electricity. In 1960, large hydropower stations produced 56% of French electricity but virtually all sites were already exploited. Coal and oil-fired power stations were developed until the 1973 oil price shock which led to the all-out development of nuclear energy. That improved the French balance of payments because oil would have to be paid for in foreign currency (some €1000 per head of the population would have been needed to buy the necessary oil at $80 a barrel to produce the necessary electricity in oil-fired power stations).

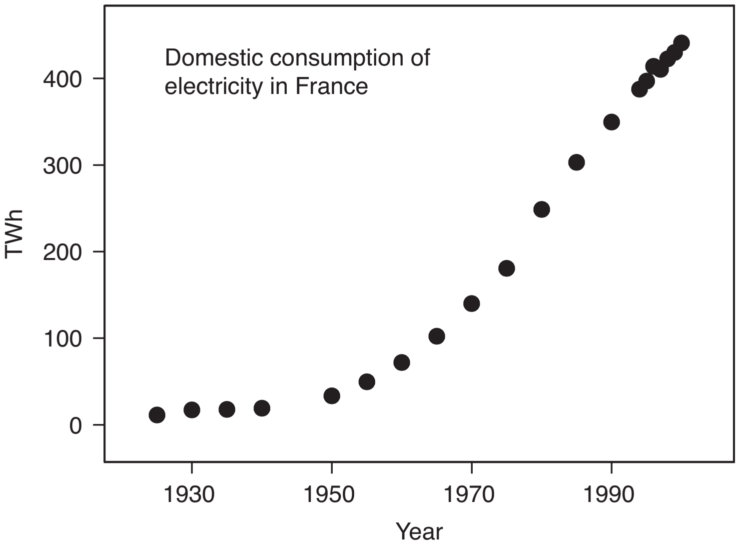

Figure 1.3 Development of domestic consumption of electricity in France [5]

Table 1.4 shows the distribution of total final energy and electricity consumption in 2005. The total final energy consumption is 160.7 MTOE as against 276.2 MTOE of total primary energy consumed in 2005.

Table 1.4 Distribution of the consumption of final energy and electricity by economic sector

	Total final energy		**Electricity**	
Sector	**MTOE**	**%**	**TWh**	**%**
Industry	37.7	23.4	135.8	32.0
Agriculture	2.9	1.8	3.4	0.8
Residential, tertiary	69.8	43.4	246.4	64.3
Transport	50.4	31.3	10.4	2.8
Total	**160.7**	**100**	**423.7**	**100**

Totals do not exactly equal 100% because of rounding errors (Source: [5, 11]).

In the next century, the world will be confronted with two fundamental problems. The first relates to cheap fossil fuel reserves and the second to the greenhouse effect.

1.5 The greenhouse effect

Without the greenhouse effect the average temperature of our planet would be −18 °C. With this phenomenon it is 15 °C. This represents an average energy difference of 150 W/m^2.[13] Since the beginning of the pre-industrial era

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[13] At the entry to the Earth's atmosphere, perpendicular to the Earth–Sun axis, the energy received from the Sun actually averages 1367 W/m^2, a value which is called the *solar constant*. The average intensity received on Earth is calculated bearing in mind that while the surface of the Earth, a sphere of radius R, equals $4\pi R^2$, the Sun only sees a disk with a surface of πR^2. The average energy received on Earth therefore equals a quarter ($\pi R^2/4\pi R^2 = 1/4$) of the solar constant, about 340 W/m^2.

The radiation balance of our planet is in equilibrium with the Sun because the energy received from the Sun is equal to that emitted by Earth. To calculate this, we use Stephan's Law which says that the energy ε emitted by surface unit of a body brought to temperature T is $\varepsilon = \sigma T^4$, or roughly $\varepsilon = \left(\frac{T}{64.5}\right)^4$ W/m^2, where σ is a constant ($\sigma = 5.674 \times 10^{-8}$ Wm^{-2} K^{-4}). Of the average 340 W/m^2 that arrive from the Sun, nearly 30% are reflected (100 W/m^2) back into space and 70% (240 W/m^2) are absorbed by our planet. Of these 240 W/m^2, 70 W/m^2 (around 20%) are absorbed by the atmosphere which is warmed and the rest (170 W/m^2, or 50%) heats the continents and oceans.

If the temperature of the Earth was –18 °C, or 255.16 K, it would emit 240 W/m^2. Thanks to the greenhouse effect, the average temperature is +15 °C which results in an emission of 390 W/m^2. As 240 W/m^2 must be emitted into space to achieve the Earth–Sun balance, 150 W/m^2 must be absorbed by the greenhouse effect of the atmosphere.

the greenhouse effect has increased by 2.45 W/m^2, or almost 1% of the energy emitted by our planet. The effect of this has been to raise the average temperature, between 1850 and 1995, by around half a degree. This increase is worrying.

Water vapour is the gas with the biggest greenhouse effect (60–70% of the total). But the amount generated by humans do not have a significant effect on its concentration in the atmosphere, and the water cycle is very rapid [10]. This is not the case with other gases like carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The halogen gases (CFC, halons, etc.[14]) are emitted in smaller quantities and their impact is minor, but their persistence is much greater. These halogen gases also play an important role in the destruction of the ozone layer that protects us from the harmful ultraviolet radiation. Measures were taken at an international level to limit their use (Vienna Convention 1985, Montreal Protocol 1987), but it will still take several decades to restore the ozone layer to its 1970s level.

The gases have different levels of greenhouse effect, which can be quantified as follows: 1.56 Wm^{-2} for CO_2, 0.5 Wm^{-2} for CH_4, 0.14 Wm^{-2} for N_2O and 0.25 Wm^{-2} for the CFCs. All fossil fuels emit CO_2 when burned, as they contain carbon. Better management of fuel combustion and the choice of fossil fuel (e.g. for the same quantity of energy generated, the burning of natural gas emits around half the CO_2 of coal) can optimise greenhouse gas emission, but it is impossible to reduce it to zero because the combustion of carbon compounds always yields carbon dioxide. By contrast, the production of renewable and nuclear energy does not contribute to an increase in the greenhouse effect.

The increase in man-made greenhouse gas emissions could have serious consequences on the environment according to a number of predictive models [10]. A number of scenarios have been developed to estimate the average temperature in 2100. They point to an average warming of between 2 °C and 6 °C. The higher values would have dramatic effects on the environment, including a notable rise in sea level, and the appearance of tropical diseases in some countries that do not have them today [10]. The Intergovernmental Panel on Climate Change (IPCC) also predicts on the basis of models that sea levels could rise by between 15 and 95 cm in 100 years, 95% of European glaciers will disappear, precipitation patterns will change (with heavier rainfall in Europe) and major climatic disturbances (cyclones, hurricanes, tornadoes, etc.) will become more frequent. These predictions are sufficiently worrying for attempts to be made at a global level for an international agreement on limiting greenhouse gas emissions. The Kyoto Conference in December 1997 made a start in this direction, although many experts consider that it did not go far enough.

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[14] The CFCs (chlorofluorocarbons) are carbon compounds in which hydrogen atoms are replaced by atoms of chlorine or fluorine. In halons, some atoms of hydrogen are replaced by atoms of bromine and/or fluorine.

1.6 Conclusion

Two factors will lead to an increased demand for energy in the future: the growth of world population and the fact that the developing countries aspire to increase their standard of living. If we assume an annual global increase of 2–2.5% in energy demand, the world's energy consumption will double within 30 years. To meet these additional needs, without adding too much to the greenhouse effect, it will be necessary to develop nuclear and renewable energies, which currently only account for 20% of the world's energy consumption.

All energy sources have their own advantages and disadvantages, in terms of cost, security of supply, impact on the environment, etc. There is no universal solution, and the best mix of energy sources will vary from country to country.

The consumption of primary energy will remain for several decades largely dominated by fossil fuel combustion, especially oil. Fossil fuels represent nearly 90% of commercial energy (80% if one includes non-commercial energy) and nothing else can replace them quantitatively or economically. Between the beginning and the end of the twentieth century, the world consumption of primary energy rose from around 1 GTOE to tens of GTOE. This is what enabled humanity to make such major strides in economic development over that period.