Chapter 7
Future prospects

The production and use of energy should increasingly be integrated into a sustainable development plan where resources are better exploited and waste and emissions are minimised. The notion of *sustainable development*, introduced in 1986 by the Brundtland Commission, is defined as development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs. In this final chapter, a number of future prospects in this perspective are examined.

For a very long time, human beings used little energy. Four hundred thousand years ago, they probably used around 0.4 kg oil equivalent (KOE) per head per day to meet food and survival needs (fire). Since the industrial revolution, human energy needs have sharply increased, and, for example, in the 1990s an American consumed some 21 KOE/day [87].

It is interesting to compare the human energy system with human's current energy needs [1]. The energy needed for a human's base metabolism develops over the course of life. At birth, in a developed country, this energy is on average 2.3 W/kg, reaching 2.7 W/kg 3–6 months later. It then reduces and stabilises around the age of 18 for about 40 years at around 1.1–1.4 W/kg. Beyond that age, it falls to just under 1 W [1]. Nearly half this energy fuels the brain and nearly a quarter the liver. A woman's pregnancy calls for additional energy of around 90 kW [1]. For comparison, 90 kWh is the energy contained in 10 l of petrol, sufficient to drive a car for some hundred kilometres.

Food produces energy of around 2.7 kWh/day. A French person's electricity consumption is around 20 kWh/day, which with other forms of energy leads to a total consumption of around 50 kWh/day.[1] It is as though modern man has about 20 slaves to help him throughout his life, but this is probably an underestimate, since many of the appliances we use were made on the other side of the world. The energy for their manufacture was consumed there and the associated waste and pollution were generated there. The energy for transport must be added, which in modern society has huge energy requirements. For example, the four engines of a Boeing 747 in flight have a

[1] These estimates were calculated from the fact that the total electricity consumed in France in 2000 was 88 MTOE out of the total consumption of 215.7 MTOE.

power of 60 MW, which corresponds, for a flight of 10 h, to a consumption of 600 MWh [1].

7.1 Fossil fuels

Fossil fuels will still be used long into the future. Further progress needs to be made in oil recovery. To extract rates of more than 50%, techniques of drilling in all spatial directions must be improved and better imagery must be developed to understand the conformation of oil wells, and fluids for making the oil less viscous [82].

The other challenge is to be able to capture and store the carbon dioxide produced in power stations. Experiments are already under way [83]. In Norway, 1 Mt of carbon dioxide is injected annually from the Sleiper offshore gas platform in the North Sea into a saline aquifer 1000 m deep. In Canada, some 5000 tonnes of carbon dioxide from a coal gasification plant are injected into a disused oil field located 300 km away. Other projects propose the burying of carbon dioxide at great depths in the ocean, but that could have an impact on the acidity of the surrounding sea.

The sequestration of carbon dioxide in deep, underground geological reservoirs would enable it to be stored for tens of thousands of years, but potential dangers need to be taken into account, such as an unexpected large-scale release of the gas.[2]

Carbon dioxide sequestration is the most expensive step: the cost of capturing and compressing the gas is estimated at between 30 and 60 €/t [97]. Transport costs around 3.5 €/t per 100 km. Injection and storage would add 20 €/t for a quantity of 1 Mt/year but might fall to 7 €/t for sites storing 10 Mt/year. Carbon dioxide capture uses energy that reduces the efficiency of energy production by an equivalent amount. Consequently, more carbon dioxide is released for the same amount of electricity produced. Various routes have been proposed for capturing carbon dioxide:

- The first is at the post-combustion stage, which would enable it to be applied to current power stations. The carbon dioxide has to be separated by a scrubber from the other exhaust gases.
- The second consists in employing oxy-combustion, which involves combusting coal in an enriched oxygen environment using pure oxygen extracted from the air (which requires energy). The exhaust gases then contain 90% of carbon dioxide that is easier to separate.
- The final route is capturing in pre-combustion where the idea is to capture the carbon dioxide before combustion, when the fuel is manufactured. For this, the initial fuel is reformed with steam (steam reforming) or oxygen

[2] The carbon dioxide released by the volcanic lake of Nyos in Cameroon in 1986 caused 1600 deaths.

(partial oxidation) to produce a synthetic gas (blend of hydrogen and carbon monoxide).

7.2 Renewable energies

The most important objective for renewable energy sources is to make them economically competitive (when they are not so already) and deal with their intermittent nature to be able to draw on energy at all times. By 2020, solar photovoltaic energy will most probably supply 1 billion people. Studies are under way on the feasibility of producing large quantities of energy in the deserts (5% of their surface could generate enough energy to supply the entire planet). The short- and medium-term objective for renewables is not to replace fossil fuels but to substitute for them where possible so as to reduce their consumption. It is also important that a country should make the best use of the renewable resources available to it. There is no universal solution and each case must be looked at on its own merits. Solutions for a new house are not the same as for a renovated property and the technologies to be used will depend on the climate and the region.

Marine energy was mentioned in Chapter 3 on renewable energies. Offshore wind farms are already a reality, but there are other possibilities that could be exploited in the future.

Wave energy (around 1 W/m^2, 45 kW/m of coast) is highly diluted and not yet economically viable. France has a good potential compared with some other countries. On the North Atlantic coast, which is particularly suitable, wave energy could generate electricity for a current price of around 8 euro cents per kWh.

The thermal energy of the oceans is potentially 100 times higher than that of tides or waves (it is estimated at 10^{13} W) [30]. The principle is to use the temperature difference between the ocean surface (25–30 °C in the Tropics) and the water at great depths (7 °C at a depth of 600 m for example). The difference must be more than 20 °C for it to be worth exploiting, and efficiency is low (2%).

Preliminary studies are also being made into how energy could be obtained from osmotic pressure arising from the difference in ionic concentration between seawater and fresh water.[3] This property is already exploited by nature because it drives the thermohaline circulation that is the second motor of the oceanic currents. With fresh water, osmotic pressure is much higher.

Heat pumps, which have existed for many years, will no doubt be further improved. They can be considered as a renewable energy source insofar as a large part of the energy they provide comes from renewable resources. They

[3] Just as two bodies with different temperatures equalise when they are placed in contact, two solutions of different concentrations placed in contact have the tendency to equalise their levels of dilution. The variable called chemical potential plays the role that temperature plays in the first case.

work by extracting heat from cold and low temperature sources and producing a fluid sufficiently warm to be used to heat a house or a building, for instance. As the spontaneous transfer of heat from a cold source to a hot source is not possible, outside work is needed to do it, and this is exactly what a heat pump accomplishes. This type of device can be considered as an energy amplifier since by using 1 kWh of energy, the heat pump can generate 3–4 kWh of heat. The difference between what is supplied and what is consumed is taken from the external medium that may be air, water or soil. In the latter case, it is called a geothermal heat pump.

Other more futuristic ideas being examined include the collection of solar energy in space. Orbiting solar power stations were first proposed in 1968. The idea is to place a solar panel of several km^2 in geostationary orbit at 36,000 km altitude. In space, solar radiation is not attenuated by the Earth's atmosphere, and the panels can be manoeuvred to face the sun. Some eight times more solar radiation would be received per surface unit. Microwaves, electromagnetic radiation similar to that used in a microwave oven or a mobile telephone, could be used to transmit this energy to the Earth, with an efficiency of around 50%. However the energy density carried by the microwaves should be sufficiently weak so as not to cause danger to living beings, which implies the need for considerable areas of radio batteries to store the energy.

7.3 Nuclear power in the future

Nuclear energy produces electricity without increasing the greenhouse effect. It is highly concentrated since 1 g of fissile matter releases around 1 MWJ, or 24 MWh. The reactors of the future, designed in a sustainable development perspective, will need to satisfy the following five conditions:

1. They must be competitive in their generating cost compared to other energy sources. The technology chosen must provide as short as possible return on investment. They must be able to operate for a long time, typically 60 years, and they should be easy and cheap to maintain.
2. Progress in improving safety in the nuclear industry is regular and constant, so they will be safer.
3. They will need to extract the maximum amount of energy from the fuel.
4. They will minimise the production of waste and will be capable of burning part of the spent fuel of the previous generation of reactors.
5. They will need to minimise the risks of proliferation.

Bearing in mind these constraints – and especially those relating to resources and their optimal use – fast neutron reactors are the best solution. Like slow neutron reactors, they may use different technologies. An example of this type of reactor is the Superphoenix developed in France but abandoned for political reasons. Discussions and studies are currently under way at the international level within the framework of the Generation IV International Forum (GIF) [98].

Among the possible solutions, we will briefly describe one to illustrate the problems posed.

The first thing to be done is to increase the efficiency of electricity production. To do this, the thermodynamic efficiency needs to be increased by raising the operating temperature of the reactor. At present, due to Carnot's theorem, the thermodynamic efficiency of a PWR is 33%, and 2 kWh of heat is released into the environment for every 1 kWh_e produced.[4] To increase the efficiency, the reactor must operate at a *high temperature*.

Unlike thermal neutron reactors that only use some 0.5–1% of the energy contained in the uranium, fast reactors can extract more than 100 times. Existing uranium reserves would supply nuclear energy produced by them for more than 10,000 years. This more efficient use of the fuel also reduces the amount of waste, partly because the natural uranium is better used and partly because some of the minor actinides are burnt in the reactor. However, it is not possible to extract all the energy in the fuel at one time. The fuel must be recycled, that is *reprocessed*. This takes us on to *fast neutron reactors*.

The coolant in a fast neutron reactor can be a gas (He or CO_2), sodium or lead–bismuth, which absorbs little or none of the neutrons. The simplest architecture is to function in direct cycle (a single circuit). At present PWRs have two circuits: the primary, in contact with the fuel core sheath, and the secondary circuit. Boiling water reactors, which have only one circuit, seem, other things being equal, to have an advantage from their direct-cycle architecture (no steam generator, for instance). Sodium fast reactors are more complex, with three circuits, two of sodium and one of water. A fast direct-cycle reactor using gas as a coolant is an interesting solution. Helium would be a good choice because of its chemical and nuclear inertia, but its low density excludes specific high energies.

The other advantage in using a gas as a coolant is the possibility of developing turbines based on the combined-cycle gas turbines that are an important element in the competitiveness of gas (efficiency above 55%).

The use of high-temperature fast reactors implies serious constraints on the types of fuel used and on the construction materials. The integrated fast neutron flux will also be important. Extremely strong materials will be needed. The fuels will need to be refractory, high-yielding, resistant to radiation and capable of being reprocessed.

To show how well fast neutron reactors fit into a programme of sustainable development, let us take the example of a PWR generating 1400 MW recently commissioned in France. After 40 years' operation, there will be some 7000 tonnes of depleted uranium from the enrichment necessary to make fuel, 1000 tonnes of uranium for reprocessing and 11 tonnes of plutonium. These nuclear materials

[4] A fast neutron reactor like Superphoenix operated at a higher temperature and its efficiency was higher, around 45%.

could be used as fuel in fast reactors to provide an equivalent amount of electricity for more than 5000 years instead of 40 years.

To develop nuclear energy at the industrial level, two cycles are possible: uranium and thorium. The uranium cycle was chosen. The fissile nuclei are Uranium-235, which exists in the natural state, and Plutonium-239 and Pu-241, which are artificial. The uranium cycle can be started easily. In the thorium cycle it is U-233, with a half-life of 160,000 years, which is fissile, and it has to be synthesised from Th-232, which is fertile. The thorium cycle is interesting as it produces shorter-lived waste. However, the reprocessing of the waste is very complex because it contains radioactive isotopes emitting gamma rays with an energy of several MeV, which must be protected against. Thorium is more abundant than uranium in the Earth's crust and could be used once uranium deposits are exhausted. Uranium and thorium together represent energy reserves for tens of thousands of years at a competitive cost. Thorium is more readily available than uranium for manufacturing a nuclear weapon but once made it can be more easily detected.

7.4 Energy in the home

Around 43% of the final energy produced in France in 2004 was used in homes for heating, air conditioning, the production of domestic hot water and various electrical appliances [90]. Energy consumption in the domestic-tertiary sector has greatly increased over the years, from only 28% of final energy in 1949. Around one-third of the energy is consumed in tertiary sector buildings and two-thirds in individual homes.

Individual homes are thus a major contributor to energy consumption – and also to emissions, since they contribute 21% of all greenhouse gases in France, corresponding to around 550 kg of carbon per person per year.

In France, there are around 30 million dwellings, and 400,000 new buildings were completed in 2005. Buildings are only renewed over about a century – a long time compared to the constraints necessary to fight climate change. The renovation of old housing stock is thus of prime importance, and this renovation needs to be done without moving the inhabitants out.

Buildings built before 1975 had poor energy characteristics. On average, 328 kWh/m^2/year was needed for heating and 36 kWh/m^2/year for hot water. New regulations have reduced these figures. Thus, from 2000, new buildings should only need between 80 and 100 kWh/m^2/year for heating and 40 kWh/m^2/year for hot water. The target today should be 50 kWh/m^2/year for heating and 10 kWh/m^2/year for hot water. Despite all the improvements in construction methods, the past weighs heavily and the average energy consumption in French homes today is 210 kWh/m^2/year for heating and 37.5 kWh/m^2 for hot water [90].

Homes are also closely linked to transport. There is no point in having a low-energy home if you need to travel 100 km a day to get to work and back. It would be better to live in a less efficient home closer to one's work. Similarly, while it is good to have pilot buildings of high environmental quality or having positive energy (producing more energy than they consume), it is more effective to make energy improvements of around 10% in tens of thousands of homes. The mass effect is primordial in home energy efficiency as in transport.

The energy solution depends on various parameters, so there can be no general rule. The aim however must always be to reduce the consumption of energy produced by fossil fuels. For a new house, for example, it is worth installing a passive solar panel that will provide hot water and some underfloor heating. In renovations, the use of heat pumps can often be advantageous but the choice of the cold source will depend on local conditions. For instance, an air–air heat pump can be used in the Paris region where the temperature rarely falls below $-15\,^{\circ}\mathrm{C}$, but in colder regions a geothermal pump, taking energy from underground, would be more appropriate.

Attention must be paid to insulation, exposure, lighting and household appliances if realistic energy economies are going to be made. The consumer has a strategic role to play in reducing energy consumption in an individual home.

7.5 Transport

Transport – especially road transport – is still expanding rapidly. In 1950, there were about 50 million vehicles in the world; by 2006, there were around 800 million. Speed, too, is at a premium: in 1880 it took 60 days to cross the Atlantic, today it can be done in 7 h.

It is difficult to foresee exactly what transport will be like in the future, because technological breakthroughs can change the solutions that we imagine today. Current thinking is that hydrogen will be the future energy vector associated with fuel cells of the PEMFC type. That presupposes two breakthroughs: one of the fuel and one on the means of using it. The interim solution is to improve current fuels before using them.

Even if the fuel cell and hydrogen are potential long-term solutions, they are still a long way off. Several decades of research are needed to reduce the cost of the fuel cells and improve their reliability. Hydrogen needs new infrastructures for its manufacture, storage and transport, which will take a long time to put in place. As mentioned earlier, the use of fuel cells in vehicles also creates problems of heat evacuation, operation at low temperatures and supply of catalysts, etc.

Bearing in mind the extensive experience of vehicles using internal combustion engines acquired over more than a century, it may be that the best solution for the next 10–20 years or possibly longer is the *hybrid vehicle* in which a petrol or diesel engine is used in conjunction with an electric motor running from a battery that can be recharged through the mains, with a backup charge from the combustion engine. Hybrid vehicles already exist (more than one million Toyota Prius have been sold worldwide) but the battery is the weak point since it cannot be recharged from the mains. In this car the battery is charged by the engine and the process of braking also charges the battery. It improves the energy management, based on the use of the battery as a back-up, which enables this car to reduce its energy consumption. In town, with traffic congestion, fuel consumption is halved compared with a petrol vehicle of comparable size and power, and can easily average 5 l/100 km. With rechargeable hybrid vehicles using batteries that provide power for about 40 km, most journeys could be made using electrical energy, since in most cases commuter journeys are no longer than this.

In France, one could imagine a medium-term scenario for reducing greenhouse gases based on the use of hybrid vehicles, a small proportion of biofuels and on electricity entirely produced by hydro and nuclear energy.

Although hydro and nuclear power stations produce around 90% of French electricity, 10% is derived from burning fossil fuels to meet peak demand, which leads to an average carbon dioxide emission of 72 g/kWh or around 30 Mt of CO_2/year. On the other hand, transport is responsible for nearly a quarter of French energy consumption (around 50 MTOE) and depends entirely on oil.

The electric vehicle has not yet caught on because of its low range (around 100 km). Also its speed is lower and its price is around 15% higher than that of a normal car. On the other hand, it is quiet and non-polluting (the pollution is made by the generation of electricity that of course can be very polluting). The cost of using these cars is low: they need around 15 kWh for 400 km, or less than two euros. If all French vehicles were electric, some 75 TWh of electricity would have to be generated, representing the output of about 10 nuclear reactors of 1 GWe. A technological breakthrough in battery design could however give the electric vehicle much wider use.

With a hybrid car, the electric motor is used for short journeys in town. On the open road, either motor can be used according to the conditions and the state of the batteries.

Biofuels can never replace the entire amount of oil used by transport because there has to be a choice between driving and eating. However, some can be produced and this results in a reduction of greenhouse gas emissions. Biomass can be gasified and artificial fuels can be made by hydrogenating these gases using the Fischer–Tropsch process. This method requires, for the same quantity of biofuel produced, a smaller cultivated area than the traditional method, although part of the energy is transferred to the manufacture of hydrogen. For current levels of transport, 100 Mt of biomass would be needed plus 250 TWh of electricity to produce the hydrogen. This corresponds to 35 nuclear reactors and 20 million hectares (in France there are 18.3 million hectares of arable land). Using fallow land (1.4 million hectares) and an equivalent area of arable land, 20% of vehicle fuel could be produced and therefore greenhouse gases could be reduced by 20%. In this case, the energy from seven nuclear reactors would be needed to produce the hydrogen.

If vehicles recharged their batteries on the electric mains for 30% of their energy needs, around three additional nuclear reactors would be needed.

With seven additional nuclear reactors, all French electrical requirements would be met without having to use fossil fuel power stations to meet peak demand.

With ten additional nuclear reactors, it would be possible to meet all France's electrical needs and supply part of the energy requirements of hybrid vehicles. During off-peak hours, they would recharge their batteries and it would be possible to manufacture the hydrogen necessary for the treatment of biomass and the production of synthetic fuels.

With this solution, no more carbon dioxide would be emitted for the production of electricity, and oil consumption and road vehicle emissions would be halved.

7.6 Thermonuclear fusion

The solar energy that reaches us from the sun comes from nuclear fusion reactions taking place in its interior. The force of gravitation in the star's core is such that the densities and temperatures needed to set off thermonuclear reactions are available. Scientists have been trying for decades to induce similar fusion reactions for the production of energy, but this was only successful with the H-bomb. Fusion is not yet safe to produce large quantities of energy for industrial needs. This objective will perhaps be attained during the course of the next century, if research currently being undertaken at an international level is successful.

The fusion of two light nuclei, such as deuterium and tritium, releases more energy per nucleon than fission. Thus, the reaction (D–T) that describes the fusion of deuterium ($D = {}^{2}_{1}H$) and tritium ($T = {}^{3}_{1}T$):

$$ {}^{2}_{1}H + {}^{3}_{1}H \rightarrow {}^{4}_{2}He + n + 17.6\,MeV \tag{7.1} $$

releases 17.6 MeV. The nucleus of helium (${}^{4}_{2}He$) takes 3.5 MeV and the neutron (n) 14.1 MeV. The energy released in fission is 0.85 MeV/nucleon (= 200/236) whereas that released in fusion is 3.5 MeV/nucleon – four times larger.

Other fusion reactions are possible. The reaction D–D can occur by two routes of equal probability:

$$ {}^{2}_{1}H + {}^{2}_{1}H \rightarrow {}^{3}_{2}He(0.8\,MeV) + n(2.5\,MeV) \tag{7.2} $$

$$ {}^{2}_{1}H + {}^{2}_{1}H \rightarrow {}^{3}_{1}H(3\,MeV) + {}^{1}_{1}H(1\,MeV) \tag{7.3} $$

They are more difficult to achieve than the (D–T) reaction because the probability of interaction is around 100 times smaller between 1 and 100 keV, which explains the preference for the (D–T) system.

Deuterium is a stable isotope of hydrogen present on earth. Tritium on the other hand is a radioactive nucleus not existing in the natural state with a half-life of 12.3 years. It is synthesised from ^{6}Li by the reaction:

$$^6\mathrm{Li} + n \rightarrow {}^4_2\mathrm{He} + {}^3_1\mathrm{H} \tag{7.4}$$

Fusion is much more difficult to achieve than fission. In fission, neutrons can easily approach and penetrate uranium nuclei because there is no electric charge, but it is much more difficult to make two light nuclei fuse because both are positively charged and repel each other. This does however occur in the Sun (but very slowly[5]) where hydrogen is transformed into helium at temperatures of 10 to 15 million degrees. This fusion is called *thermonuclear* because it is induced by the kinetic energy of thermal agitation of the nuclei. There are attempts to harness this phenomenon to produce energy far into the future.

Thermonuclear fusion is achieved within a deuterium–tritium plasma.[6] For thermonuclear fusion to occur, the following conditions must be met:

- A very high temperature to enable the ions to overcome the electrostatic repulsion keeping them apart. The temperature necessary for D–T fusion is around 100 million degrees Kelvin (10^8 K).
- High particle density to ensure a large number of collisions between the ions.
- A long confinement time, so that the density and temperature of the plasma remain high and a sufficient quantity of fuel fuses.
- Confinement without contact because no material can resist such extreme conditions.

The balance of power of a fusion reactor is positive if it satisfies the Lawson criterion. This translates, for the D–T fuel heated to 10^8 K, by the equation $n \times \tau_E > 10^{20}$ s/m^3, where n is the particle density in the plasma and τ_E the energy confinement time. The objective of the research is to achieve *ignition*, in other words a self-sustaining reaction. The condition of ignition is given by $n_0 T_0 \tau_E > 6 \times 10^{22}$ (m^{-3} MJ K s), where n_0 and T_0 are respectively the density and temperature at the centre of the plasma and τ_E the energy confinement time. Two routes are possible to achieve thermonuclear fusion:

1. The *Tokamak*, originally developed in the USSR, consists in confining the hot plasma within a torus by a magnetic field that prevents it from touching the walls of the chamber. This route would appear to be the most promising for developing an industrial fusion reactor. The research is international, and the International Thermonuclear Experimental Reactor (ITER), currently being built at Cadarache in France, will replace the Joint European Torus (JET) that is the biggest tokamak to be built so far.[7]

[5] Fortunately, or else the Sun would quickly exhaust its fuel.
[6] A plasma is a state of matter in which electrons are detached from atoms, resulting in a cloud of electrons and ions.
[7] Its plasma volume is 140 m^3 and its performance is such that $n_0 T_0 \tau_E = 9 \times 10^{20}$.

2. *Inertial confinement fusion* for that the most promising route is to use high-energy laser beams to compress and heat D–T fuel enclosed in glass microspheres. The inertial confinement results in a higher particle density during very short periods of time. This process is more suitable for the simulation of nuclear weapons than energy production. Even though more energy is produced at the level of the microsphere than is injected, the efficiency of the laser bundles is so low (only a few per cent) that in total more energy is consumed than is produced.

In a fusion reactor based on magnetic confinement, 80% of the energy produced is taken up by the neutrons that are absorbed by a blanket surrounding the reactor. This blanket contains lithium, enabling tritium to be produced that can be used as a fuel. The blanket needs to be about a metre thick, because the fusion neutrons are very energetic (14.1 MeV). They heat the blanket as they slow down, and this energy is recovered through a coolant.

The amplification factor Q is the ratio between the energy produced by the fusion reactions and the injected external power. If $Q > 1$, the fusion reactions will provide more energy than was injected. *Break even* describes a state where $Q = 1$, when the energy produced by the fusion reaction is equal to the energy injected into the plasma. In this situation, α particles provide part of the plasma energy. In a fusion reactor, the aim is to achieve ignition, the situation when the energy from the fusion reactions compensates for the losses and there is no need to supply further energy. The plasma burns like a candle and continues burning until the fuel is exhausted. When ignition occurs, Q is infinity, because the external energy is zero.

Wastes produced during fusion are essentially the activation products of the enclosing structures that have the advantage of having short lives: they are harmless after about 100 years. On the other hand, the tritium must be carefully contained because it can easily be dispersed into the environment. The advantage of a fusion reactor is that it cannot get out of control and can be stopped very quickly.

As far as reserves are concerned [85], deuterium is fairly abundant. In seawater, there are 33 g/m^3, which translates into reserves of 4.6×10^{13} tonnes. At current rates of energy consumption, this would be sufficient to outlast the life of our planet (5 billion years). The same is not true of lithium. Natural lithium is made up of 92.5% ^{7}Li and 7.5% ^{6}Li. Its concentration in the Earth's crust is around 30 g/m^3, and reserves are estimated at 12 Mt, or three times as much as uranium. Lithium is also found in seawater (uranium also, incidentally) at a concentration of 0.17 g/m^3 that gives reserves of 240,000 tonnes. A 1000 MWe fusion reactor would consume in a year 100 kg of deuterium, 150 kg of tritium and 350 kg of lithium in the blankets to breed the tritium. There are terrestrial lithium reserves for about 5000 years. There would be enough lithium extracted from seawater to last several million years, which is still short compared to the Earth's life expectancy. D–D fusion will therefore need to be developed and brought into use.

ITER is a major research establishment. Its role is not to produce electricity but to master the conditions for creating a thermonuclear fusion plasma. The ITER reactor will be eight times bigger than the current JET international reactor, based in the UK. Whereas JET has a gain of 1, ITER will have a gain of 10, but this will still be insufficient for industrial electricity generation that requires a gain of 40. ITER's power is 500 MW_{th} and the plasma will be confined for a maximum of 400 s. The original project, 20 years ago, aimed at a power of 1500 MW_{th} and a confinement of 1000 s. The JET international machine, in England (currently the world's largest tokamak), and the Euratom Tore Supra (the world's largest superconducting tokamak) situated at Cadarache in the Rhone Valley in France served as models in the preparation of the ITER project.

Several stages are still needed before it will be possible to build an industrial fusion reactor to generate electricity for consumers. Energy must be produced reliably and continuously and at an economically competitive cost. First, a prototype reactor, currently called DEMO, with a power of 2000 MW_{th}, will enable a gain of 40 to be made and allow further studies into the production of tritium from blankets, the extraction of energy, etc. Finally, a third reactor, called PROTO, with a power of 1000 MWe, will become an industrial prototype. Bearing in mind the duration of each project (several decades) and their cost, it seems unlikely that large-scale electricity generation could be started before the next century. However, if there was international consensus that a new form of energy was essential, the development time could no doubt be shortened.

7.7 Energy storage

A technological breakthrough in this area could completely change the energy landscape. Currently, the largest amounts of energy are stored in hydro barrages through pumping water uphill with off-peak energy. This allows several GW to be stored. Large-scale compressed air storage is another solution.

Batteries can certainly be improved, but progress is likely to be marginal rather than a breakthrough. Al–air or Zn–air fuel cells may have a future using Al or Zn as energy vector. Hydrogen is also, as we have seen, an attractive means of storage, especially for renewable energies.

Superconducting magnetic energy storage (SMES) systems already exist enabling high-quality electrical power of 1–10 MW to be supplied. Their principle is to store energy in the magnetic field created by a current circulating in a superconducting magnet that is kept at the temperature of liquid helium in a cryostat, which consumes energy. Research is being carried out into the development of systems from 10 to 100 MW.

There are also two more futuristic methods of energy storage that are worth describing briefly.

The energy released in elementary nuclear reactions is measured in MeV, a million times higher than for chemical reactions. The question arises whether it would be possible to have some kind of 'nuclear' storage. A solution could be found in nuclei that possess states of high spin or isomeric configurations. Some nuclei have states situated a few MeV above the fundamental state and live long enough to be used. For instance, the nucleus of ^{178}Hf has a half-life of 36 years in a state situated 2.4 MeV above the fundamental state. Another, ^{198}Re, has a life of 300,000 years and would be capable of storing 1 TJ/l for several thousand years [86]. While this means of storing energy is understood, recovery on demand is more problematic. This would require being able to modulate the half-life of the nucleus. If this could be done, and if the process could be generalised to other nuclear excitations, which is far from evident, it would also be possible to resolve the problem of nuclear waste by reducing the half-life of long-life isotopes.

Antimatter does not exist in the world in the natural state and therefore cannot be a source of energy, but it could be used to store energy. However, in the present state of research, it would be necessary to provide infinitely more energy (around 10^8 times more) to produce the antimatter that could be later recovered.[8] The storage of antimatter in magnetic bottles also requires energy and could be dangerous if there was a confinement breakdown. And even if it were possible to store large quantities of antimatter, there would still be the problem of recovering the energy released in the form of highly energetic photons.

7.8 Negawatt-hours

Energy is abundant and cheap in developed countries. This leads to waste. However, large number of people are still in a state of energy poverty. An Ethiopian, for example, consumes on average 320 times less electricity than a French person. Sustainable development requires control of energy consumption and economies. Providing the same service with a smaller amount of energy should be the constant objective. These watt-hours that are not consumed may be described as negawatt hours.[9] These are the least polluting since they were never produced.

There are now electronic gadgets that help manage energy systems intelligently and make substantial economies. Their falling cost should enable them to be used more frequently.

Some estimates of the quantity of energy that can be saved are given below. Many other examples can be found in Reference 87.

An estimate of the energy needs for heating and air-conditioning of a standard dwelling of 100 m^2 and 250 m^3 volume is 14,300 kWh/year. If the

[8] The production of a billionth of a gram (10^{-9} g) in 10 years at CERN cost several hundred million euros.

[9] The term negawatt is also used but this refers to a power. It does not give an idea of the quantity of energy saved. A low energy lamp bulb of 20 W that replaces an ordinary 100-W bulb for example creates 18 negawatts but does not give a real idea of the economy achieved, since a 100-W bulb only consumes energy when it is switched on.

house is built facing the right direction, some 34% of the energy can be saved (9420 kWh) and the same house ecologically designed would use 65% less energy (5070 kWh) [87].

For heating a house, an electric convector heater converts 1 kWh of electricity into heat, whereas a heat pump can produce, according to the external temperature, around 3–4 kWh of heat for 1 kWh of electricity consumed [87].

A traditional fireplace has an efficiency of between 10% and 15%. With a simple heat exchanger, efficiency can reach 25% and up to 50% with a reverse exchanger. Closed fireplaces for new buildings or insets for existing fireplaces have an efficiency as high as 70–80%. There also exist high-performance stoves that are less polluting and have an efficiency of between 70% and 80% as opposed to 40% for older models. Wood burning boilers[10] today can be almost as efficient as heating oil or gas boilers (85%) [87].

Solar thermal energy is not yet sufficiently used despite its many advantages. It can be harnessed through special glass and well-designed verandas, wall-mounted panels, solar hot-water heaters or underfloor heating. Individual micro-generation of electricity can also be a solution to energy needs by modulating the proportion of heat and electricity generated.

Lighting in the residential-tertiary sector account for 14% of the consumption of electricity in France. Traditional incandescent light bulbs have a very low efficiency (5%) with 95% of the energy being lost in the form of heat.[11] The effectiveness of lighting can be measured in lumens per power unit. An incandescent light bulb has an output of 13 lumens/W, a halogen lamp 14 lumens/W, long-lasting compact fluorescent bulbs 60 lumens/W and fluorescent tubes 63 lumens/W. Electroluminescent diodes are another possible future solution for lighting.

The choice of domestic appliances is important in achieving energy economy. Cold appliances (refrigerator, freezer) represent the largest energy drain for a family,[12] followed by cooking appliances (hotplates and electric oven). Paradoxically, using a dishwasher with cold water intake uses less energy (20% less) and much less water (40–75% less) than washing up by hand [87].

Figure 7.1 shows the annual consumption of some domestic appliances used in a French home.

Finally, there is the problem of keeping appliances on standby (television sets,[13] video recorders, etc.). As they are on around the clock, their consumption is far from negligible. With an estimated total of around 50 W per household, it amounts to around 10 TWh/year of electricity – the power generated by 1.5 nuclear reactors.

[10] Oak for instance yields more energy than poplar (1700 kWh/m^3 as against 1400 kWh/m^3).

[11] Including the efficiency in electricity production (33%), transport losses and light bulb efficiency, the total efficiency of electric lighting is only around 1.5%.

[12] An American style refrigerator (with ice cube maker) uses four times as much electricity as a European model.

[13] Watching a television with a power of 80 W for 3 h/day uses 240 Wh. If it is left on standby mode (15 W) for the remaining 21 h, it will use an additional 315 Wh.

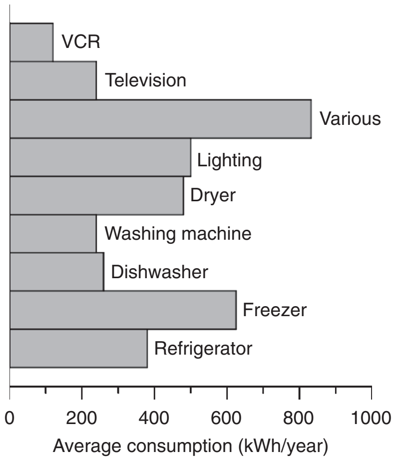

Figure 7.1 *Average annual consumption of typical appliances in a French home. By introducing low-energy appliances, the total consumption could be virtually halved. [Source: www.ademe.fr]*

7.9 Conclusion

Human beings have sufficient imagination and resources to develop new sources of energy when they are needed. The period that we are currently living in, where energy is abundant and cheap, unfortunately does not encourage economy or long-term research investment. It is clear that energy will become increasingly expensive in the future, and that long established habits must be changed to adapt to the new situation.

All human beings must have access to energy because it is the motor of economic development. For this to happen, energy needs to be cheap and its use should have a minimal effect on the environment. The cost of energy is a major limitation because, out of the 6 billion people in the world, 2.8 billion have less than $2 a day to live on.

The renewable energies, which humans have used since they discovered how to control fire some 500,000 years ago, are on the whole still too expensive, unreliable and too low powered. Fossil fuels (coal, oil, gas) on which our modern civilisation depends will gradually become scarcer, and other sources of energy will have to be found to replace them. Nuclear energy (uranium or thorium fission, deuterium–tritium fusion) could supply energy for tens of thousands of years. Renewable energies (provided energy needs are not too high) would be capable of supplying enough energy to last the 5 billion years before the Earth disappears. Deuterium–tritium fusion, once controlled and developed, could supply considerable quantities of high-power energy.

Better utilisation of energy, increasing conversion efficiency, and the selection and better management of energy systems is indispensable for future sustainable development.

In the future, we will need more electricity to meet new needs. For example, heat or cold could be supplied using heat pumps using the temperature source best adapted to requirements (air, ground or water), or rechargeable hybrid vehicles would enable peak demand for electricity to be smoothed by being mainly recharged at night. Moving part of our energy consumption onto electricity is only attractive when it is produced without release of greenhouse gases, that is, with nuclear, renewable energies or possibly fossil fuels if the carbon dioxide released can be captured and stored. Carbon capture on an industrial scale is far from being perfected, and it would take thousands of plants like the existing prototypes (1 Mt of CO_2/year) to sequestrate a significant proportion of the carbon dioxide currently released by human activities.

In the more distant future, it will be important to make best use of the carbon atoms extracted from nature (remaining fossil fuels or biomass). In particular, they need to be used to manufacture liquid fuels for transport and other purposes where they are indispensable. And they should not be burnt to provide energy for transformation processes and should be prevented from releasing carbon dioxide. This means that external heat sources that do not release greenhouse gases (renewable or nuclear) should be used, and that hydrogen, produced from water by electrolysis using clean electricity, should be harnessed to achieve balanced chemical reactions.