Chapter 1

Nuclear fusion and the energy problem

1.1 Prospective of the energy use growth

The principal driving forces determining how energy use will evolve in the future are world population, growth of economy, technology, and social behaviour and values. According to the World Bank's population projection [Bos92], the population is expected to nearly double between 2001 and 2100, and development must continue particularly in the South. Most of the population doubling will be in developing countries, where even today two billion people still do not have access to commercial energy. Providing them, and the almost six billion more people expected by 2100 with access to convenient energy, will make the primary energy use to grow strongly through the XXI century.

But global progress in technology and social values on a world scale must result in reducing energy consumption per person, representing a contrary force to the growth of primary energy use. A very useful indicator of both the level in technology and social behaviour and values is the intensity of energy, defined as the amount of energy used to produce a euro's worth of gross world product. In the developed countries, the energy intensity has stabilized and has even been slightly reduced. This is very important for the control of carbon emissions and consequently for the mitigation of climate change.

In 1998 the International Institute for Applied Systems Analysis (IIASA) and the World Energy Council (WEC) completed a study where three alternative cases for the future of the global energy, which covers the period through 2100, were analysed [Nak98]. The first prediction (case A) corresponds to an ambitious economic growth with impressive technological improvements. Case B describes a future with less ambitious technological improvements and a moderate economic growth. Finally, case C presents an ecologically driven future, including both substantial technological progress and unprecedented international cooperation centred explicitly on environmental protection and international equity.

In the IIASA-WEC study, the gross world product in 2100 will be 10, 11 and 15 times higher than that of 1990, for cases B, C, and A, respectively, and the energy intensity will be reduced from 0.8% per year in case B, 0.9-1.0% per year in case A, and 1.4% per year in case C. Note that only one model for population growth [Bos92] is considered (see the insert plot in Fig. 1.1). The reason for this is that different scenarios would lead to demographic considerations which would not help significant conclusions to be reached.

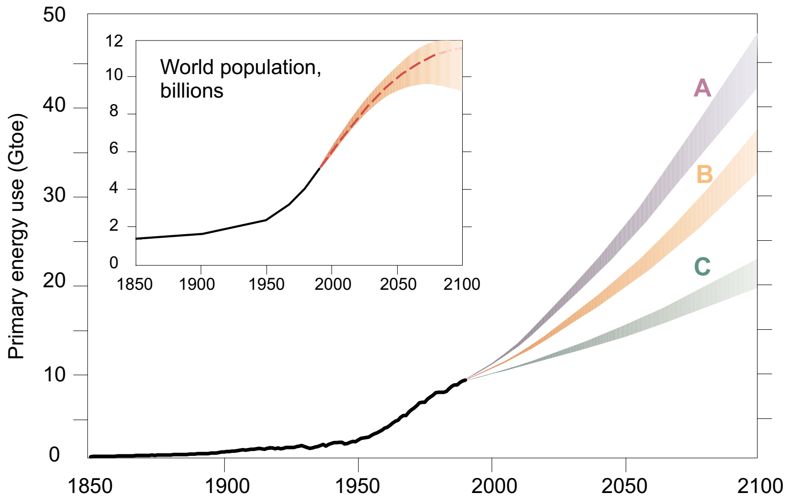

Figure 1.1: Evolution of the use of global primary energy in gigatons oil equivalent (Gtoe), for three prediction cases. The insert figure shows the global population growth (historical and predictions) in billions of people (Source: Ref. [Nak98]).

Fig. 1.1 presents the historical and prevision evolution of global primary energy use for the three cases considered in the IIASA-WEC study. As a first conclusion, the primary energy use grows substantially in all the predicted cases. In case A, the primary energy use in 2100 will be five times what it was in 1990. In cases B and C, it will be four and 2.3 times, respectively, the 1990 value. However, this growth of primary energy use is lower than that of gross world product.

Secondly, there is a significant shift toward energy forms which reach consumers in increasingly flexible, convenient, and clean forms, such as the electricity form. As an example of this trend, the final energy supplied by grid (electricity, gas, hydrogen, and district heat) will evolve from about 25% at present to approximately 60% in 2100, for all the considered scenarios. It can thus be said that the electricity demand will grow even more than the global primary energy use.

Another important result of such a study is that only ecologically driven scenarios (case C) and a particular scenario of the high growth case A, where the fossil fuels are in progressive diminution, lead to compliance with the international proposals for the stabilization of the atmospheric CO_2 concentration (Kyoto Protocol and the UNFCCC[1] objectives).

As seen in Fig. 1.2, the atmospheric concentration of CO_2 has remained, at least for the last thousand years, at a level of about 280 ppm. Since the beginning of industrialisation (around 1800) it has risen to more than 360 ppm (increasing about 25%). There is a general agreement among specialists that this fact will cause the average temperature on earth to rise. The consequences of this increase in temperature are, however, very difficult to evaluate. At present, nobody can ascertain whether, even by shutting down all sources of CO_2 immediately, there is any guarantee that the whole ecosystem will return in a reversible way to the previous situation.

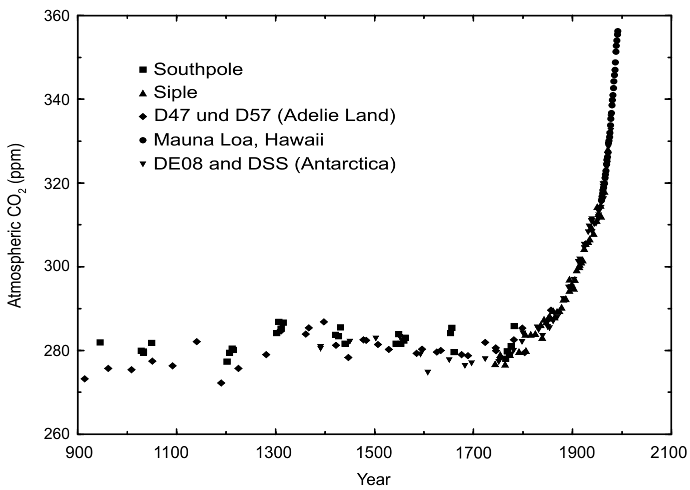

Figure 1.2: Evolution of the CO_2 concentration in the atmostphere (in ppm) during the last 1000 years (Source: Ref. [Joo96]).

What the consistent scenarios with the stabilization of carbon emissions have in common is, firstly, significant technological progress particularly in energy end-use, and, secondly, a shift from fossil to non-fossil fuels.

1.2 Primary energy sources

As can be seen in Table 1.1, about 86% of the primary energy in the world was produced in 1999 by burning fossil fuels (i.e. oil, natural gas, and carbon) [EIA99].

[1]United Nations Framework Convention on Climate Change (UN, 1992)

Table 1.1: Contribution of the main energy sources to the primary energy production in the world.

Energy source	Primary energy production (%)
oil	39.4
natural gas	23.9
coal	22.3
hydroelectricity	7.1
nuclear fission	6.6
others (renewable)	0.7

The number of conceivable non-fossil fuel candidates which should substantially contribute to an energy production in agreement with the control of CO_2 emissions, is very limited: renewable resources, nuclear fission, and nuclear fusion.

Although renewable energy resources in the world are inexhaustible, unfortunately they seem to have only a limited potential due to their low energy density and fluctuations in time. Nuclear fission energy is presently subject to an unfavourable social opinion, mainly due to the problem associated with the storage of long-term highly radioactive waste, and to the danger that arose from severe accidents such as that at Chernobyl.

1.3 Fusion energy

Fusion energy appears to be the source which meets all the future energy needs mentioned in the previous Section. First, it is able to cover future energy demands since the fuel of such an energy source is virtually inexhaustible and readily available throughout the world. Secondly, the final energy will be delivered to the consumer in the form of electricity, which is a convenient form for personal future needs and for trade possibilities. Moreover, fusion energy respects the environment and, in particular, does not emit CO_2 into the atmosphere. Finally, in addition to the environmental advantages of the fission reactors, fusion energy will offer an inherently passive safety and a low production of radiological waste (as explained below).

Fusion energy, which is the energy source that powers the stars, has its origin in nuclear fusion reactions. Like fission, it derives from the difference of binding energy per nucleon (proton or neutron) between the products and reactants[2]. In contrast to fission, where the energy is released from heavy elements, in the fusion reaction it is only released from light elements.

The most promising fusion reaction is that in which the nuclei of deuterium D

[2]Binding energy is the energy equivalent of the mass difference between a whole nucleus and its individual constituent protons and neutrons.

($^{2}_{1}$H) and tritium T ($^{3}_{1}$H) fuse to produce an alpha particle (helium nuclei) with the release of a neutron, as shown in Fig. 1.3. The energies given are the kinetic energies of the reaction products.

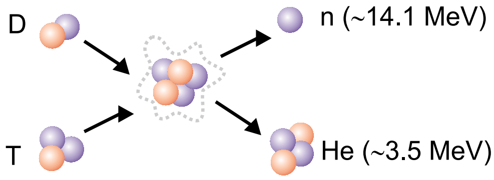

Figure 1.3: In the most promising fusion reaction, a deuterium ion combines with a tritium ion to form an unstable compound nucleus which relaxes into a helium ion and an energetic neutron.

The actual fusion reaction occurs when two nuclei meet within nuclear dimensions. Such close encounters only occur when nuclei have energy enough to overcome the Coulomb barrier, i.e. the natural electrical repulsion between the protons. Because of the quantum mechanical tunnelling, fusion reactions occur at energies somewhat lower than those required to overcome the Coulomb barrier. However, the temperatures required for the nuclei to be fusioned are very high (10 keV for the D-T reaction, i.e. more than 100 million degrees Celsius).

Deuterium and tritium are two isotopes of hydrogen. The first one (deuterium) is inexpensive and is naturally present in sea water (0,034 g/l). Tritium does not exist naturally but can be bred in a fusion system when the lithium, for which we have plentiful world resources, absorbs neutrons produced in the fusion reaction.

$$\mathrm{n} +^{6}_{3}\mathrm{Li} \longrightarrow {}^{4}_{2}\mathrm{He} + \mathrm{T}.$$

The D-T products are not radioactive elements. However, a very important task in the fusion technology development is the selection of the surrounding materials in order to minimize the activation produced by the energetic neutrons. Using advanced structural materials with low activation, as for example vanadium alloys or silicon carbides, the radioactivity after 100 years after shutdown of the reactor would fall to levels comparable to those of the ashes from power plants fired by coals [Ong00][Rae95]. But even if existing structural materials like stainless steel are used, the induced radioactivity in a fusion reactor is still about 10 times less than in a fission reactor of comparable power [Con90].

In a D-T fuel mixture, the D-D fusion reaction also occur.

$$\mathrm{D} + \mathrm{D} \longrightarrow \begin{cases} {}^{3}_{2}\mathrm{He}\,(0.82\ \mathrm{MeV}) + \mathrm{n}\,(2.45\ \mathrm{MeV}) & (50\%) \\ \mathrm{T}\,(1.01\ \mathrm{MeV}) + \mathrm{p}\,(3.03\ \mathrm{MeV}) & (50\%) \end{cases}$$

These reactions do not use tritium. However, the cross-section of this reaction is not significant except at very high temperatures. On the other hand, the D-$^3_2$He reaction

$$D + {}^3_2He \longrightarrow {}^4_2He\,(3.67\text{ MeV}) + p\,(14.67\text{ MeV})$$

is very attractive from a theoretical point of view since it does not produce neutrons [Fun96]. The main difficulties for the D-$^3_2$He reaction are the very high temperature conditions and the scarceness of $^3_2$He on earth. The cross-section for all these fusion reactions are given in Fig. 1.4. It can be seen that the cross-sections of the D-D and D-$^3_2$He reactions are at least one order of magnitude lower than that of the D-T reaction, for energies which are obtainable.

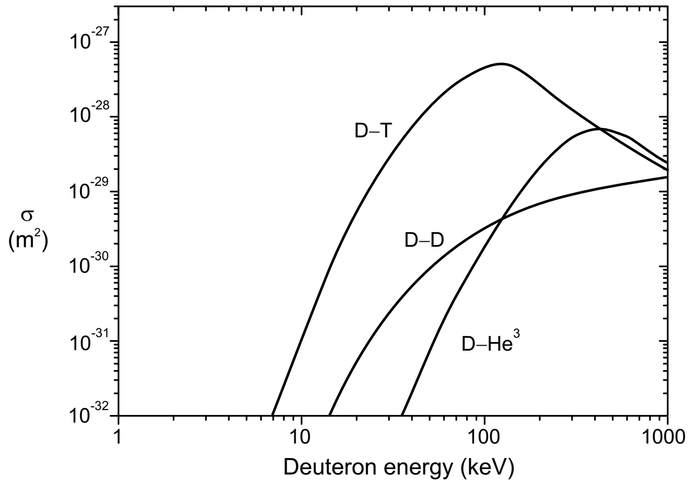

Figure 1.4: Cross-sections σ for the reactions D-T, D-D (total), and D-^{3}He as a function of deuteron energy.

The potential energy density of fusion is much larger than that of the conventional energy sources. As an illustration, complete burning of deuterons and the first generation fusion products (T and ^{3}He) results in the overall equation:

$$6D \longrightarrow 2{}^4_2He + 2p + 2n + (43.3\text{ MeV}),$$

providing about 350×10^3 MJ per gramme of deuterium. It can also be seen that one litre of water contains the equivalent energy of 300 litres of petroleum fuel.

1.4 Thermonuclear fusion by magnetic confinement

At the temperatures required for the D-T fusion reaction (over 100 million degrees Celsius) the fuel has changed from gas to plasma. Since plasma consists of two types of charged particles, ions (atomic nuclei) and electrons, magnetic fields can be used to isolate the plasma from the vessel walls. Two experimental approaches to bring about fusion reactions are being studied: fusion by magnetic confinement, in which plasma is confined by magnetic fields, and fusion by inertial confinement, in which a tiny fuel capsule is highly compressed. Only the magnetic confinement will be considered here.

In a magnetic field the particles spiral along the field lines. Magnetic configurations can be divided into closed and open configurations, depending on whether the field lines are closed or not. In the open configurations, particles are confined inside a finite space by magnetic mirrors that increase locally the magnetic field and reflect the particles back. The closed magnetic concepts, which are the most advanced for the thermonuclear controlled fusion, are generally toroidal devices (ring-shaped), in which the plasma is confined away from the toroidal vessel walls by helicoidal magnetic fields.

The principal magnetic field in a toroidal device is the toroidal field (i.e. going in the direction of the torus). But due to geometrical considerations, this magnetic field is stronger in the inner part of the torus than in the outer part. The resulting magnetic field gradient creates a vertical electric field due to ions going up and electrons going down. In order to avoid a horizontal drift of particles out of the plasma due to the interaction of the magnetic field with the vertical electric field, a poloidal magnetic field (i.e. going round the poloidal cross-section) is necessary. The combination of the toroidal field and poloidal field gives rise to magnetic field lines, which have a helical trajectory around the torus. This trajectory is drawn on a so-called magnetic surface. Thus, particles transit alternatively through regions of high and low magnetic field.

There are several types of confinement systems to produce these required helical magnetic field lines. The main types are the tokamaks and the stellarators. In a tokamak, the toroidal field is created by a series of coils evenly spaced around the torus, and the poloidal magnetic field is produced by the current in the plasma itself, this current flowing in the toroidal direction, and by the current in the poloidal field system. By the ohm effect, this current also heats the plasma. In a stellarator, the helical lines of force are produced by a series of coils which are themselves helical in shape.

During the last few years an important effort has been made to develop large stellarator devices, for example the projects W7 in Germany, LHD in Japan, and the TJ-II in Spain (Fig. 1.5).

The tokamak concept

The tokamak option is the confinement system concept which has come closest to achieving the performances required for a commercial reactor.

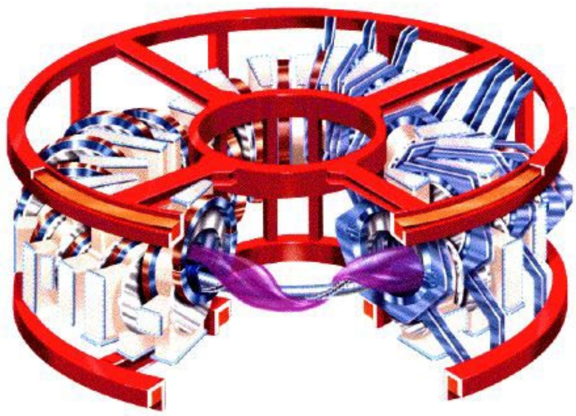

Figure 1.5: Magnetic confinement system of the stellarator TJII (available at the website of CIEMAT: http://www-fusion.ciemat.es).

The easiest way to induce the plasma current necessary to create helical magnetic fields in a tokamak, is by a transformer action in which an electric field through the torus is created by varying a magnetic flux. The operation of such a configuration is, therefore, inherently not continuous in time. This mode of operation, mostly used in present-day tokamaks, is called inductive mode of operation. Fig. 1.6 shows the basic components of a tokamak magnetic confinement system, in which the poloidal magnetic field is generated by a transformer action. Additional coils around the outside of the vacuum vessel, not shown in the diagram, shape and position the plasma.

An alternative way of generating the plasma current using several current drive methods using waves or neutral beams, is being investigated in some present-day experiments. If the whole plasma current is driven by these methods, the transformer action is no longer required and we can have a steady-state operation which is interesting for a commercial fusion reactor.

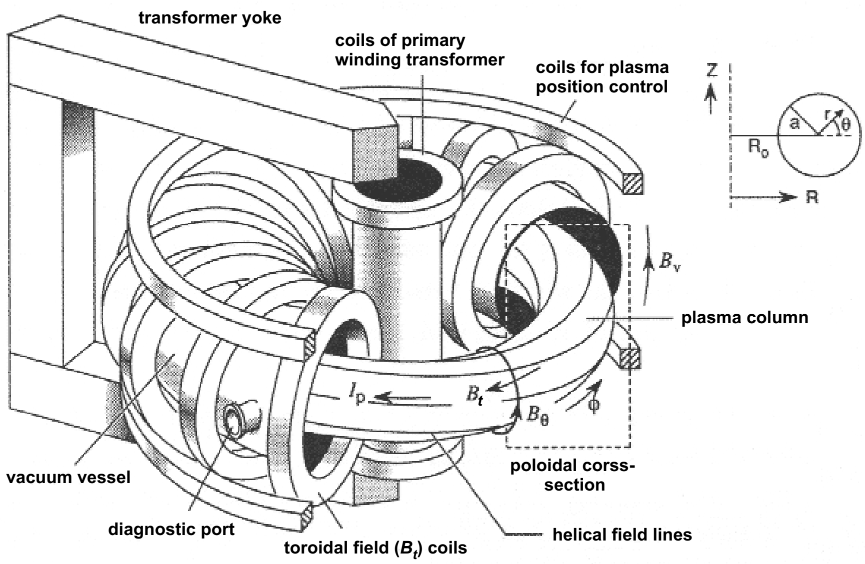

Figure 1.6: Schematic diagram of the magnetic confinement system of a tokamak.