The potential of fusion as a future source of energy

Le potentiel de la fusion comme une source d'énergie

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Abstract

The objective of fusion research is to harness this potential source of energy and help meet mankind’s future energy needs. Fusion has key features which make it an attractive option in a future energy mix: inherent safety; environmentally benign; no emission of greenhouse gases; and capacity for large scale energy production. The required raw materials for the fuel are abundantly and widely available around the world. These features gives fusion the potential to make a substantial contribution to satisfying world energy demand later this century and beyond.

The next step in fusion research is the international ITER project, which has to demonstrate the scientific and technological feasibility of fusion energy by generating 500 MW of fusion power. The partners in the project are the EU, China, India, Japan, Korea, the Russian Federation and the USA, together representing more than half of the global population. ITER will be constructed in Europe, in the South of France, and should start operation in about 10 years. It should be followed by a demonstration power plant that will deliver the first electrical power to the grid and open the way to commercial fusion energy.

Abstract (french)

L’objectif des recherches sur la fusion est d’offrir à l’humanité une nouvelle source d’énergie quasi inépuisable. La fusion offre de nombreux attraits: sécurité d’exploitation, faible impact sur l’environnement (pas d’émission de gaz à effet de serre ni de déchets radioactifs a vie longue), sa capacité de produire d’importantes quantités d’électricité, réserves de combustible abondantes et bien réparties sur tous les continents. La fusion pourrait donc offrir une contribution essentielle dans le cadre d’un développement durable.

La stratégie de développement de la fusion comporte une dernière grande étape expérimentale, le projet ITER. Son objectif est la démonstration de la faisabilité scientifique et technologique de la fusion. ITER générera une puissance de fusion de 500MW sur une durée de 500s à 3000s. Les partenaires du projet sont l’Union Européenne, la République Populaire de Chine, l’Inde, le Japon, la Corée, la Fédération de Russie et les Etats-Unis. ITER sera construit en Europe, dans le sud de la France. Son exploitation scientifique devrait débuter dans 10 ans.

ITER sera suivi par un prototype de démonstration qui intégrera les technologies du réacteur électrogène et produira déjà une importante quantité d’électricité, ouvrant le chemin à la commercialisation de l’énergie de fusion.

1 Introduction

With an increasing world population and a growing economy, the demand for energy is sure to grow. New solutions will be required for providing a targeted answer to both the energy demand and the environmental problems associated with our present energy system. The research on nuclear fusion, the energy source of the sun and the stars, has seen remarkable progress over the last decades and is close to move out of the laboratory: the agreement to build the ITER project, which aims at demonstrating the scientific feasibility of fusion as an environmentally friendly source of energy, has just been signed. ITER is the main element of a research programme which aims at making fusion a credible energy option for clean, large-scale power generation for the second half of this century.

This paper presents the main features of fusion, its potential contribution to a future sustainable energy mix and discusses the current status and future strategy of research towards large-scale fusion power plants.

2 Fusion on Earth

2.1 The fusion process

In a fusion reaction, two light atomic nuclei fuse together to form heavier ones, as is shown in figure 1. The fusion process releases a large amount of energy, which is the power source of the sun and the stars. In stars, heavier elements are formed by consecutive fusion reactions starting from hydrogen.

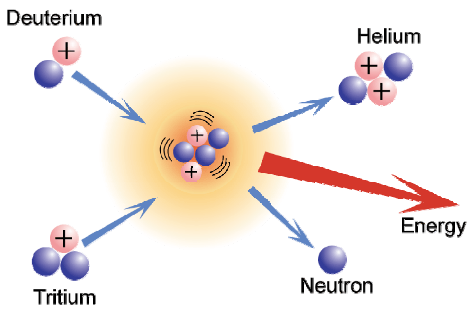

Figure 1: An example of fusion reaction. Two nuclei, here deuterium and tritium, fuse together to form a helium nucleus and a neutron. A large amount of energy is released in the form of kinetic energy in the helium and the neutron.

A fusion reaction does not happen easily. The nuclei of atoms have a positive electric charge, and repel each other. But if the two nuclei manage to get close enough together in spite of the repelling force, the attractive nuclear force comes into play and leads to the formation of new atoms as shown in figure 1. Therefore in order to achieve fusion reactions, the particles have to move very fast to overcome the electrostatic repulsion. This can be achieved when the temperature is extremely high, e.g. of the order of 15 million degrees in the sun or hundreds of millions degrees in a fusion reactor on Earth. At these temperatures, the state of matter is called a “plasma”: the negatively charged electrons are separated from the positively charged atomic nuclei, and together they form a gas of charged particles, in which they move independently. Plasmas are very common in the universe, stars being made of plasma. On earth, natural plasmas can be seen in lightning or boreal auroras and artificial plasmas in neon bulbs for example.

The origin of the energy released by fusion reactions is linked to the famous Einstein equation $E = mc^2$ relating energy and mass. Fusion reactions, such at shown in figure 1, give rise to lighter elements, the difference of mass being released as kinetic energy. A single fusion reaction releases an enormous amount of energy, millions of times more than a single chemical reaction. One kilogram of fusion fuel can generate the same amount of energy as 10.000.000 kilograms of coal. An electricity generating power plant working on this principle will therefore only need a very small amount of fuel.

2.2 Deuterium-tritium fusion

Although many different fusion reactions are possible, only a few of them are interesting as an energy source on earth. Among the reactions that require the (relatively) lowest temperatures, i.e. around 100 millions degrees, the easiest to achieve on earth is the reaction between deuterium and tritium, two isotopes of hydrogen, shown in figure 1.

Deuterium is the stable isotope of hydrogen, with one extra neutron in its nucleus, tritium is the unstable isotope of hydrogen, and has two extra neutrons. To produce enough fusion reactions, the deuterium-tritium mixture, the plasma, has to be brought to a temperature of 100 to 150 million degrees, ten times higher than the temperature in the core of the sun.

2.3 Confining a hot plasma

As there are no materials that can withstand such a high temperature, a way must be found to keep the hot plasma away from the walls of the plasma vessel. Furthermore, if the plasma would touch the wall, the plasma would cool down and fusion would stop. To isolate the plasma from the walls, a strong magnetic field is applied. The charged particles in the plasma follow the magnetic field lines, which can be organised in a circular way, such that the plasma does not touch the inner wall of the vessel. This technique is called *magnetic confinement*. In modern fusion experiments, the plasma is confined in a doughnut-shaped vessel with magnetic coils. The most advanced device is called a *tokamak*, as shown in figure 2.

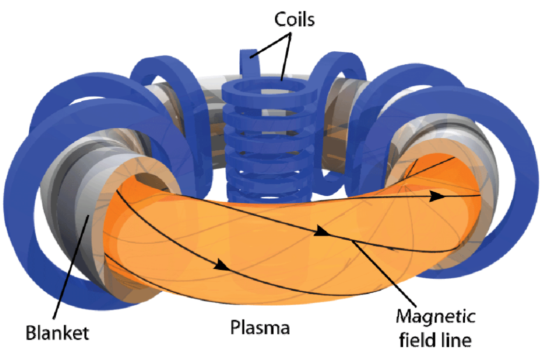

Figure 2: The principle of a tokamak. The plasma is contained in a doughnut-shaped vessel, also called a 'torus'. Using superconducting coils (blue) a magnetic field is generated, which causes the plasma particles to run around in circles, without touching the vessel wall. In reality, a number of other coils are present, witch produce subtle changes to the magnetic field.

3 Fusion as an energy source

When will fusion become available as an energy source, what will be its characteristics? Will it be clean and safe? What is the waste, and how large is a typical unit? These often posed questions will be answered below.

3.1 Principle of a fusion reactor

Before answering these questions, it us useful to understand the main principles of a fusion power plant. These plants are expected to burn deuterium and tritium in fusion reactions. The tritium fuel will be produced within the plant, where lithium will be turned into tritium. Therefore the primary fuels brought from outside will be deuterium and lithium. The energy released by the fusion reactions will be used to produce high grade heat, as in a conventional nuclear fission reactor. This, in turn, is used to generate electricity, or, possibly, produce hydrogen.

3.1 Fuels

Fusion is a particularly attractive energy source as it uses fuels that are abundant and available around the globe. As mentioned above, the primary fuels are deuterium and lithium. Deuterium is a hydrogen isotope, which can be readily extracted from water (there is around 33g of deuterium in every cubic metre of water), and lithium is an abundant light metal — for example used in lithium-batteries — from which tritium can be generated inside the reactor. The lithium from one laptop battery, combined with the deuterium from 100 litres of water, can produce 200.000 kWh, covering the electricity use of an average European citizen for 30 years.

3.2 Safety

Fusion power plants will be inherently safe. Although the plasma in a fusion power plant will have a volume of 1000 cubic meters or more, the total amount of fusion fuel in the vessel is very small: only two grams, enough for just a few seconds of operation. If the fuel supply is closed, the reaction stops without problems within seconds. Fusion is not a chain reaction and can therefore not run out of hand: it is indeed very challenging to produce and sustain the reaction and any deviation from optimal conditions will lead to a decrease in the reaction rate.

Tritium is a radioactive substance, and fusion power plants are constructed in such a way that a safe handling of the tritium is ensured, which is subject to appropriate laws and regulations. Techniques and expertise to handle tritium safely already exist. The assessment of safety in power plant models shows that there is no conceivable fusion accident which would necessitate the evacuation of the surrounding population.

As tritium is produced inside the plant in a closed circuit, the total amount of tritium present can be limited to about 1 kg. Outside the plant, no transport of tritium is needed, except for a new fusion power plant, which needs to be 'primed' with tritium the first time it is used; after that it can produce its own supply.

3.3 Environmental impact

Fusion is one of the CO_2 free energy options for the future, and has another important potential advantage: fusion reactions produce no long-lived nuclear waste. Indeed the "ash" of D-T fusion reactions is helium, an environmentally friendly inert non-radioactive gas.

On the other hand, the highly energetic neutrons produced by the D-T reactions will activate the structural materials of the vessel. After closure of the reactor these materials will have to be disposed of. However, if proper materials are used, the half life of the resulting waste can be limited to about 10 years, meaning that after a period of 100 years the radioactivity drops to a value of one 10.000th of its initial value. Studies recently carried out forecast that almost all, and possibly all these materials can be recycled after 100 years or less. The development of low-activation materials with good properties in a neutron environment, which are needed for this aim, is therefore an important and active part of the international fusion research.

3.4 Costs of fusion power

In April 2005, EFDA has released the *European Fusion Power Plant Conceptual Study* (PPCS). The study defines four future fusion power plant models illustrative of a wider range of possibilities, spanning from near-term to very advanced, and addresses questions related to safety and environmental impact, economics, and development needs[1].

In the study, the costs of future fusion electricity were computed from detailed plant models using well-attested industrial costing techniques. Although cost estimates so far ahead are highly dependent on technological and financial assumptions, the study concluded that the cost of electricity from the models (5-10 Eurocents per kWh, depending on the model) is in the range of estimates for the future costs from other renewable sources, obtained from the literature.

Another important feature is the fact that most of the cost relates to capital amortisation. Therefore the cost of fusion-based electricity is expected to be less sensitive to economic or political events than oil, gas or coal based electricity, whose costs are dominated by the cost of primary fuels.

4 The contribution of fusion to a sustainable energy mix

We live in a world that has only just *begun* to use energy. During the last four centuries, the global population has increased by a factor ten to the present 6.5 billion, mainly due to revolutions in agriculture, industry, hygiene and medicine. According to the United Nations, the global population will continue to grow during the next 50 years to around 9 billion people, of which a large share will live in regions that presently have a very low standard of living, such as most of Asia and Africa.

4.1 Our energy use increases

As economic growth is urgently necessary to bring much of the world out of poverty, the worldwide energy demand is foreseen to increase during the next 50 years by as much as a factor of 2. It is an enormous challenge to supply the world population with safe, affordable, and, above all, *sustainable* energy. At the same time there is increasing pressure to substantially reduce atmospheric pollution, most notably of carbon dioxide. Together, these conflicting goals drive a need to produce enormous amounts of non-carbon energy supply, much greater than our total present energy supply. This presents a huge challenge. A challenge that does not have one single solution: all viable energy sources that can contribute to a sustainable energy mix should be developed as soon as possible, and supported with the appropriate allocation of funds.

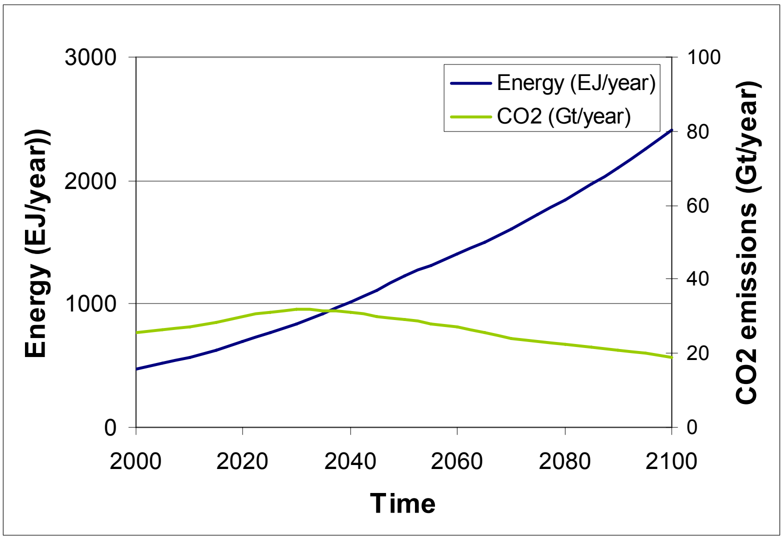

Figure 3: To stabilise atmospheric CO_2 concentrations at 550 ppm requires a progressively stronger decoupling of energy and carbon emissions over this century.

There are many technologies which can be brought to bear on this problem; fusion is only one of them. Nonetheless it is instructive to look at the issues and timescales to see how fusion may contribute. Figure 3 shows a result from modelling reported by the IPCC: this shows the contradiction between the need to stabilise the atmospheric CO_2 concentration at 550 ppm, and the expected increase in energy demand [2]. Around 2040 the mid-term challenge is already to halt the growth in CO_2 emissions in spite of the increasing energy demand; beyond that there is the even greater challenge to substantially reduce CO_2 demand whilst still meeting an increasing energy demand.

4.2 The potential contribution of fusion

The current developmental path towards commercial fusion power foresees the demonstration of large-scale electricity production by a demonstration power plant (called DEMO) roughly 35 years after the decision to construct ITER, with commercial use of fusion power following in the decades after that. If this programme is successful, fusion should start to contribute to world energy production in the second half of this century.

Due to reasons inherent to the fusion process, the size of a future fusion power plant will be about 1000-1500 MW electrical power output, which is in the same range as base-load power stations today. Therefore, fusion power plants would be suitable to deliver large-scale base-load power The supply of large base load electricity will be increasingly important with the increase of the urban population in the future.

Often, the criticism can be heard that "Fusion will not come in time". From figure 3, it should be clear that the need for CO_2-free energy sources is not restricted to the next few decades, but that it will be a pressing issue for the rest of this century.

In conclusion, fusion power, if successfully brought to the market, has strong potential benefits as a contributor to a sustainable energy system, particularly in a future energy market with reduced carbon emissions. Fusion has enormous fuel reserves, sufficient for thousands up to millions of years of world energy supply, with very low atmospheric emissions.

5 The current status of fusion research

5.1 Rapid progress

In the few decades that research on nuclear fusion has been carried out, enormous scientific and technological progress has been made. Fusion scientists now manipulate plasmas of hundreds of millions of degrees, in large fusion devices.

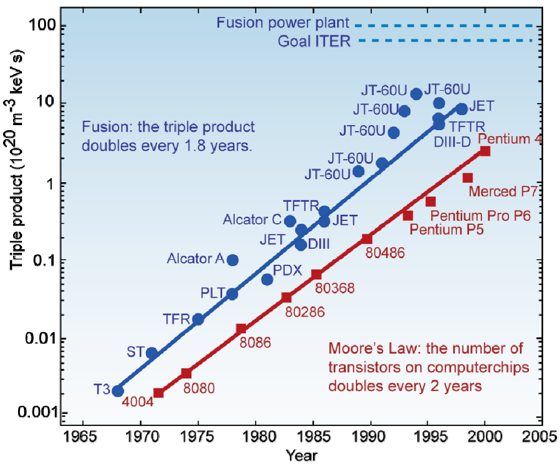

Figure 4: The progress of fusion research through the years, measured by the so-called "triple product" (density x temperature x confinement time), which is an indication of the performance of a fusion plasma. Please note the logarithmic scale on the vertical axis. For comparison, the development of computer chips is indicated.

Figure 4 shows the progress of the so-called 'triple product', a figure-of-merit which measures the performance of a fusion plasma. The progress is comparable to that of computer chips (Moore's law). The triple product has seen an increase of a factor of 10.000 in the last thirty years, while only another factor of 6 is needed to arrive at the level required for a power plant. This last step is expected to be achieved on the ITER project which will follow the successful JET project.

5.2 The Joint European Torus

The Joint European Torus (JET), based in Culham, Great Britain, is the central research facility of the European Fusion Programme and the largest tokamak in the world.

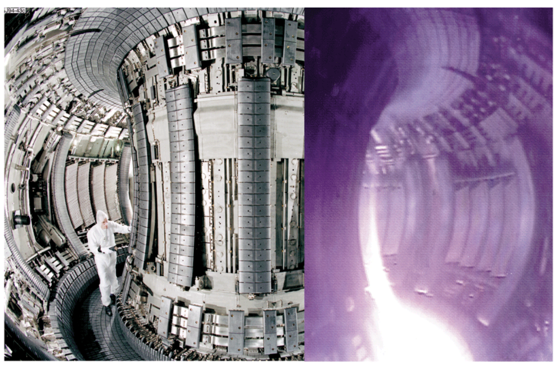

Figure 5: A look inside the plasma vessel of the Joint European Torus (JET). JET is located in Culham, UK. The plasma is shown on the right.

JET has produced significant fusion power in deuterium/tritium plasmas — up to 16 MW — in short pulses, limited only by the technical features of the experimental device. 'Breakeven' conditions, where the fusion output power equals the external input power required to heat the plasma, were almost reached. Moreover, JET has demonstrated that fusion devices can be operated safely with tritium fuel and that activated structures can be maintained and modified using remote handling techniques.

Thanks to the success of JET and other experiments, the world fusion community is now ready to take the "Next Step" of constructing a larger device, ITER, which will produce plasmas under reactor conditions of high power gain and provide a reliable basis for proceeding to a demonstration reactor, capable of producing electricity.

5.3 The ITER project

While significant progress has been made with JET and other fusion experiments, it was clear from an early stage that a larger and more powerful device would be needed to create the conditions expected in a fusion reactor and to demonstrate its scientific and technical feasibility. ITER is an international research and development project with the aim to demonstrate the scientific and technological feasibility of fusion energy.

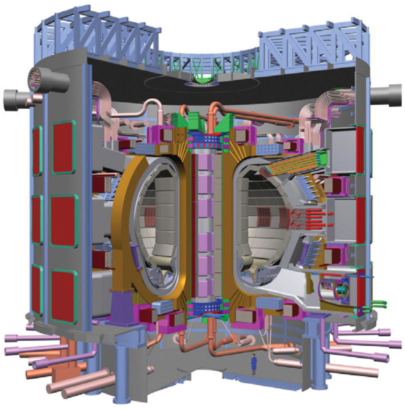

Figure 6: The ITER machine. The man in the bottom shows the scale.

ITER will be a machine of the tokamak type in which the torus-shaped fusion plasma is confined by strong magnetic fields (see Fig. 6). The device's main objective is to demonstrate prolonged fusion power production in a deuterium-tritium plasma. Compared with current conceptual designs for future fusion power plants, ITER will include most of the necessary technology, but will be of slightly smaller dimensions and will operate at about one-fifth of the power output level.

ITER has twice the size of JET in its linear dimensions (see figure 7), which means it has a plasma volume that is almost ten times larger. This size has been chosen in order to achieve a high gain in power: one expects a factor 10 or more amplification of the input power used to initiate the fusion reaction in the plasma. It will therefore be the first fusion experiment to produce net thermal power and will open the path towards fusion based power plants.

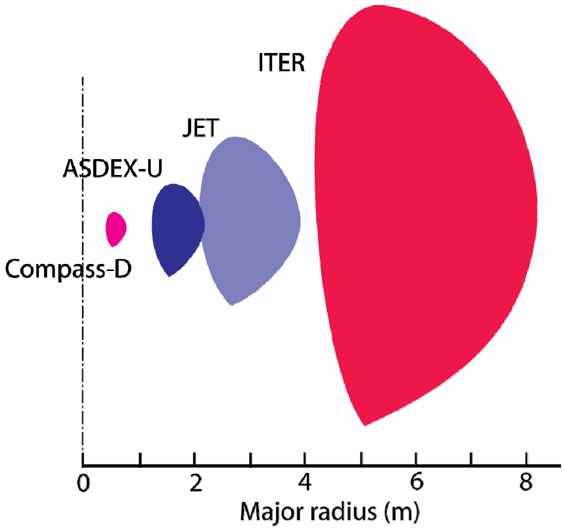

Figure 7: the size of the plasma in different fusion experiments across Europe. The ITER plasma is twice the size of JET in its linear dimensions.

ITER is still an experimental device. It will allow the study of plasmas in conditions similar to those expected in a electricity-generating fusion power plant. With its 500 MW of fusion power produced for extended periods of time (up to 3000s), it will also test a number of key technologies for fusion including the tritium breeding technologies, plasma heating, control, diagnostic and remote maintenance that are expected to be needed for a real fusion power station.

ITER is truly a global project: the current partners in the ITER project are Europe, Japan, the Russian Federation, China, India, Korea and the USA. In June 2005, the partners in the project decided unanimously to choose the European site at Cadarache, in the South of France, as the location for the construction of ITER. The ITER Agreement has been signed in Paris on 21 November 2006. The construction should start soon and the first plasma operation is expected in 2016.

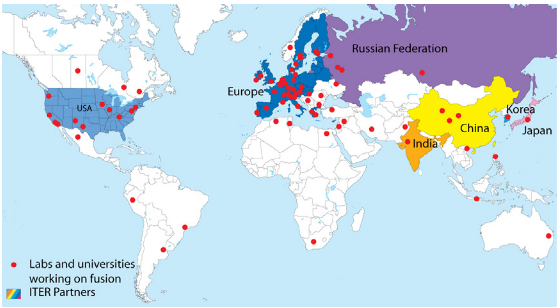

Figure 8: Countries participating in the ITER project. The dots indicate fusion research institutes.

The construction costs of ITER are estimated at 4.7 billion Euro over 10 years, a large part of which will be awarded in the form of contracts to industrial companies. Another five billion Euros are foreseen for the 20-year exploitation period. Europe will contribute a major share of the costs. The contributions of the partners to the construction will for the largest part consist of components for the machine, so-called *in kind* contributions.

More information on the ITER project can be found in the paper by the ITER Organization presented at the WEC 2007 Conference.

6 A strategy towards fusion power

The long-term aim of fusion research and development in Europe is to create power station prototypes demonstrating operational safety, environmental compatibility and economic viability. The strategy to achieve this long-term aim includes a number of different elements: first of all the development of a larger experimental device, ITER, followed by a demonstration reactor called *DEMO*. DEMO should demonstrate the technical feasibility, potential reliability of operation and economic attractiveness of fusion energy, and should serve as a credible prototype for a commercial power plant. Concepts for future fusion power plants need to be developed as well, in order to guide the development of DEMO.

In addition, the strategy includes the study of improved concepts for future fusion devices, and accompanying physics and technology R&D activities, which also involve European industry. Finally, studies are performed on the socio-economic aspects as well as the safety and environmental aspects of fusion power, which focus on the potential contribution of fusion to sustainable base-load power generation.

Mid-term plans

The EU and Japan have come to an agreement to work together on projects, in particular the design of a high-tech materials testing facility, which will complement research in ITER and set the basis for the construction of a future demonstration fusion power plant DEMO. Three projects are currently foreseen under this Agreement, which goes under the name of "Broader Approach".

The first is the engineering design of the **International Fusion Materials Irradiation Facility** (IFMIF), which will allow testing and qualification of advanced materials in an environment similar to that of a future fusion power plant. The second is the Japan-EU **"Satellite" Tokamak Programme**. During ITER construction, major experimental facilities will be required to develop operating scenarios and address key physics issues for an efficient start up of ITER experimentation and for research towards DEMO. For this purpose, the JT-60U tokamak in Japan will be upgraded to an advanced superconducting tokamak and used by Europe and Japan as a "satellite" facility to ITER. The third project is the **International Fusion Energy Research Centre**, which should co-ordinate joint activities to design DEMO and R&D activities, large scale simulation activities of fusion plasmas by super-computer and remote experimentation activities to facilitate a broad participation of scientists into ITER experiments.

Concluding remarks

Climate change, environmental degradation due to fossil fuel use, security of supply and energy poverty are all very serious issues that must be faced. The transition towards a sustainable energy supply is surely one of the major challenges of this century and all available sources will have to play a role in the future sustainable energy mix. We need to develop a full range of safe and environmentally-friendly energy options applicable to the near-term, medium- term and long-term.

With its inherent environmental and safety advantages, and the almost inexhaustible supply of fuel, fusion should be considered as an important element in any global strategy designed to implement sustainable development. As fusion is particularly suited for large-scale base load electricity production, it could be an ideal complement to renewable energy sources in the future energy mix. Fusion technology, brought to fruition, will be an asset of the utmost value to our descendants.

More information can be found on the following websites:
www.efda.org
www.jet.efda.org
www.fusion.org.uk
www.iter.org

[1] *A conceptual study of commercial fusion power plants*, Final report of the European Power Plant Conceptual Study (PPCS), European Fusion Development Agreement, April 2005
[2] IPCC Special Report on Emissions Scenarios, IPCC, 2000, ISBN 92-9169-113-5