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DIRECTORATE-GENERAL FOR RESEARCH

WORKING PAPER

THERMONUCLEAR FUSION

Current status

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Scientific and Technological Options Assessment Series

STOA 114 EN

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Executive Summary

The context and need for decision

The development of fusion technology as an energy source is a historically unique undertaking. Between the discovery of its physical mechanisms and the possible availability of commercially usable power stations there will probably be an unusually long period of around 100 years of intensive R&D. It is accordingly not possible to say definitively whether fusion research is still more a matter of fundamental research or has progressed into the stage of development of an energy technology.

Fusion experiments are becoming increasingly large-scale with a high degree of technical complexity, requiring substantial financial investment. In the light of these framework conditions, international cooperation is particularly intensive and stable. The scale of resources needed and very long period to possible implementation, with the resulting extremely great uncertainties in evaluation lead to major complexity in the pending decisions.
The community of fusion researchers believes that the reactor-oriented research programme should be continued with two intermediate phases – ITER (International Thermonuclear Experimental Reactor) and DEMO (Demonstration Fusion Powerplant) – to prepare for construction of the first commercial fusion reactor in around 2050. ITER, which currently requires far-reaching decisions, is a partnership between the EU, Japan and Russia, with other states involved. In parallel to ITER, construction of a special high-intensity fusion neutron source is needed to develop and test low activation materials. DEMO is intended to demonstrate the technical feasibility of a fusion power plant and generate electricity in continuous operation for the first time.

To achieve this programme, very substantial scientific and technical challenges must be mastered. The R&D process required will take several decades and promotional funding on a large scale. In the almost 50-year history of fusion research, the difficulties in developing a fusion power plant were repearedly underestimated, with the result that the horizon for implementation had to be pushed further and further into the future, becoming in effect a "moving target".

Nuclear fusion is also a particular challenge for technology assessment. Forecasts of the technological impacts of fusion in more than 50 years are extraordinarily difficult, and require careful interpretation. They are generally no more than heuristic approaches which might give some indication of what requires special attention in the further development process of fusion. The assessment is methodologically complicated by the fact that the quality of the numbers supplied by fusion research is very difficult to judge, given the possible wishful thinking involved and the impossibility of finding "independent" know how.

What is the cost of fusion research?

In the past 30 years, substantial public funding has been invested in promoting plasma research. In the EU almost € 10 billion was spent on fusion research up to the end of the 90s. In the last few years, around € 130 million a year has been invested in fusion research from German Federal funds. For comparison, German Federal R&D spending on renewable energy and efficient use of energy in 2000 amounted to € 153 million. Up to the point of possible implementation of electricity generation by nuclear fusion, the current estimate is that R&D will need further promotion totalling around € 60-80 billion over a period of 50 years or so, € 20-30 billion within the EU. ITER was redimensioning from the initial € 7 billion to € 3.5 billion, which will probably be spread over ten years. A decision is needed next year on implementing ITER, its possible location and the division of the costs between the participating countries.

Do we need thermonuclear fusion?

The arguments in favour of using fusion energy are primarily determined by providential considerations: first, long-term security against scarcity of energy due to exhaustion of fossil fuels, and second, limiting climatic change by avoiding greenhouse gas emissions. The starting point is the assumption – still unproven – that fusion powerplants will be commercially available from the middle of the 21st century.

All global energy scenarios are based on further growth in demand for energy. On this basis, global demand for primary energy to 2050 will rise to two to three times the level in 1990. Energy saving measures can at best slow this trend. Climate protection requires in the long term the abandonment of the use of fossil fuels. This is also desirable in terms of sustainability, as it leaves the limited fossil resources available for other uses.

In the mid-21st century, the same fuels as today will probably play the dominant role in energy supply, although in a different mix. The gap in energy supply due to the growing scarcity of fossil fuels and rising global energy demand is essentially closed by renewable fuels in many energy scenarios. It is not possible to derive from these scenarios how far the planned progressive expansion of the development and use of renewable fuels combined with the exhaustion of existing potential for energy savings will have effect in practice by 2050. Another open question is how far bottlenecks in the supply of fossil fuels will play a role in this.

Renewable fuels and thermonuclear fusion are accordingly often discussed in terms of a certain competition between them by 2050. A common feature of both options is CO_2-free transformation of energy and their classification as "future technologies", making them in principle modules in an energy supply which is independent of fossil fuels. It is entirely conceivable that the two options could coexist in energy supply, for example for reasons of climate protection or in terms of a desired level of security in supply with corresponding diversity of available technologies. There is broad complementarity in the nature of the plants as well: as centralised large-scale installations, fusion powerplants would be primarily suitable for securing the base load in urban regions. They would also fit in well e.g. in future supply infrastructures in countries currently based on coal (e.g. China, India). Renewable energies by contrast are more likely to be used in decentralised and smaller units.

A substantial advantage of energy production through thermonuclear fusion is, as noted above, that the fusion process does not generate any climate-damaging greenhouse gases. A functioning fusion technology would therefore be suitable for contributing towards avoiding climatic change in the second half of the century. However, it cannot contribute to this in the short or medium term. The level and degree of implementation of environmental and climate protection goals also have a significant influence on the structure of energy supply in 2050. If these goals are given comparatively high weighting, fusion powerplants would have to be positioned in an environment which is probably characterised by intensive use of renewable fuels and lower energy demand. This would require powerplants which can be controlled more quickly for energy and network management. Fusion powerplants – designed with more emphasis on steady long-term operation – would hardly be able to perform this function. If the goals were given comparatively less weighting, there would be more demand for low-cost (new) energy sources with rising energy demand. With CO_2-free thermonuclear fusion generation of electricity, it would be possible to supply large quantities of additional energy, but this would not be commercial competitive on the basis of our current knowledge.

Currently, there is no sign of any clear technical line of development to show which energy transformation technology or technologies will play a dominant role in 50 years (e.g. fuel cells, hydrogen technology or thermonuclear fusion). Thermonuclear fusion is one of many options for future energy supply whose use promises an additional possibility of generating base load electricity, and which is accordingly more suitable for supplying densely populated urban regions. The decisive factor in further pursuit of the thermonuclear fusion option is not its immense quantitative potential for supplying energy, but the strategy chosen for energy supply through 2050. Thermonuclear fusion is primarily a providential option for a more distant future in which fossil fuel reserves and resources are largely exhausted. It could contribute to an energy mix which is robust in the face of various political and economic developments.

Is thermonuclear fusion safe?

Fusion reactors should be intrinsically safe. A crucial difference from nuclear fission is that uncontrolled nuclear chain reactions are ruled out in fusion powerplants by the laws of physics. Even so, catastrophic accident scenarios cannot be excluded. What kind of accidents could occur, with what likelihood, and how far the radioactive materials could be released in this event, is still a matter of dispute, as this requires assumptions about reactor design. There is currently no unambiguous proof or refutation that the goal of intrinsic safety is attainable, and this proof depends on the results of R&D over a period of decades.

Destruction of a fusion powerplant by an act of war or terrorism would probably release a significant portion of its radioactive and chemically toxic materials. Assuming that the easily mobile tritium component of a fusion powerplant was fully released by some violent event, the population over several square kilometres would have to be evacuated.

Tritium is particularly important for the further development of nuclear weapons arsenals, because it is used in various advanced nuclear weapon designs. However, it is also important for the spread of nuclear weapons. Tritium is accordingly a major proliferation risk from the operation of fusion powerplants. The risk of breeding fissile materials which can be used in weapons is, however, lower overall with a pure fusion powerplant than with a fission reactor.

Is electricity from thermonuclear fusion economical?

Evaluating the economic viability of electricity from fusion compared with competing fuels and calculating electricity generation costs are highly speculative exercises. The speed of technological progress alone and trends in costs of competing (e.g. renewable) energy systems are immensely important for their competitiveness, and these are not amenable to long-term prediction. It is regarded as certain that investment will dominate operating costs in electricity generation costs. The cost of a 1,000 MW plant is put at € 5-6 billion. Fusion powerplants will accordingly be very capital-intensive major projects. This means they will be primarily suitable for centralised electricity generation for base load. Even the supporters of thermonuclear fusion expect electricity generation costs to be higher than those of competing technologies, on the basis of our current knowledge.

If the present global trend towards liberalising energy markets continues, the high capital intensity would be a major disadvantage for fusion powerplants, as it is not advantageous to tie up capital for the long term in a liberalised environment. An additional factor is that fusion powerplants would have initially to compete with reactors which are at least partly amortised and which can produce at marginal cost. Energy utilities will only accept fusion powerplants if they can expect a clear economic advantage over established technologies, including a risk premium for the still unknown capability and reliability of a young technology. It is accordingly disputed generally whether DEMO can be followed by fusion powerplants capable of economically competitive operation. Initial problems may make further government support necessary. The high level of capital intensity of fusion powerplants would be an important obstacle to use in developing and transition countries in particular.

Is electricity from thermonuclear fusion ecological?

Societal acceptance of fusion technology will depend to a great extent on appropriate consideration of environmental criteria at the point of technology decision-making. A major environmental advantage of fusion technology is that operation does not generate any climate-damaging greenhouse gases.

Conversely, the radioactive waste generated in the reactors are certainly the main radiological problem with nuclear fusion. Evaluation of these depends on the achievement of ambitious goals in further development of the technology and materials used over the next few decades. The second key radiological risk is the tritium fuel. Due to its specific properties, handling this material poses certain difficulties. Tritium is very mobile, and accordingly difficult to deal with in the event of release. The use of tritium in fusion reactors still requires solution of numerous problems and technical advances in process technology (tritium analysis, processes for decontaminating surfaces and cooling water containing tritium).

The resource situation is not an essential problem: deuterium and tritium, are currently the preferred fusion fuels and are available worldwide in large quantities. Deuterium can be extracted from sea water by electrolysis. The corresponding technologies have already been tested on a large scale. Tritium occurs naturally only in minimal amounts, and is accordingly produced by bombarding lithium with neutrons, which also generates helium. As fusion energy is stored at great density in the fuel, hardly any transportation is required. The quantities of deuterium and lithium required annually for a 1,000 MW fusion powerplant could be delivered in a single truck. This would not involve transporting any radioactive substances.

Is thermonuclear fusion socially sustainable?

Development of a virtually inexhaustible source of energy and the universal availability of its fuel makes thermonuclear fusion suitable for avoiding social conflict over resources. In addition, the strong international cooperation on fusion research is contributing to international understanding.

By contrast, major projects tend to arouse scepticism among the general public. Fusion powerplants could also run into problems with acceptance because they contain a significant quantity of radioactive material and require final storage facilities for radioactive waste.

Energy production from thermonuclear fusion will only be accepted by the general public if it meets the needs and concerns of society. Pure information or advertising measures designed to promote acceptance have essentially proved unsuitable. To avoid crises of acceptance and confidence, early and intensive dialogue without predetermined results is required between science, interest groups and the public.

What should be done?

Despite the shortfalls in knowledge and the problems of evaluation in this specific case, there is no reason to leave development of fusion energy to its own devices. No reliable evaluation is possible at present for many questions regarding if and to what extent fusion energy is compatible with the many facets of the principle of sustainability. However, it is still possible to formulate corresponding requirements and identify the conditions under which fusion development can satisfy these postulates. It is then possible to consider the potential for shaping fusion in social terms. What intervention can influence development so that these conditions can be met? Seen in this way, the following general options for action are possible for research policy. The purpose of these options is to open up the entire space of possibilities for political structuring. Concrete positioning within this space is a matter for political evaluation and decision.

"Continuation" option: further intensive research with the existing key areas, primarily following the ideas of the fusion research community. This option would track the inherent dynamism of this area of research.

"Thorough evaluation" option": comprehensive evaluation of the thematic area of thermonuclear fusion, involving external experts, using the criteria of sustainable energy supply as a guideline. The resulting design requirements could be integrated into subsequent technological development. Here, the inherent dynamism might be interrupted, up to the point of formulating steering or termination criteria if the "moving target" phenomenon persists.

"Reorientation" option: cease focusing on fastest possible development of thermonuclear fusion as an energy technology following the Tokamak route and return to a research programme focusing on a broader understanding of the scientific foundations and alternative containment concepts. This would force termination of the inherent dynamism of this area of research.

The central challenge remains of building up independent expertise and organising broad societal discourse. Given the problem that it is virtually impossible to establish direct involvement of society, due to the remoteness in time and lack of everyday experience of fusion, this is not a simple task.

CONTENTS

I. Introduction

Over the last few decades, energy consumption worldwide has risen sharply. Until now energy has been provided predominantly by fossil fuels, and we are now within sight of exhausting these resources. Moreover, when coal, petroleum and natural gas are burned, carbon dioxide is released, which has an effect on the climate. We cannot yet say with any certainty whether the strategic options of enforced energy savings and more efficient energy use on the one hand, and of increased use of renewable fuels on the other, will be sufficient in the medium and long term to provide amounts of energy that will meet the criteria of sustainable development.

In this context, nuclear fusion appears to offer an advantageous technical option: it does not generate any carbon dioxide, its potential hazards from radioactivity are well below those of a fission reactor, and the raw materials currently favoured – heavy hydrogen and lithium – are readily available.

On the other hand, reservations have been expressed: the technical feasibility of electricity-generating plants powered by fusion has not yet been proven. There is a vast need for research and development both in terms of understanding the basic mechanisms and in the area of materials, such as those with low activation and almost no tendency to become brittle even under the most extreme conditions. At present, the community of fusion researchers reckons on commercial fusion power plants being introduced around the middle of this century. The question arises as to what contribution nuclear fusion can make, under these circumstances, to solving the problems of greenhouse gases.

In many ways, the development of fusion technology as an energy source is a historically unique undertaking. Between the discovery of its physical mechanisms and the possible availability of commercial power plants there is expected to be an unusually long period of around 100 years of intensive research and development work. It is accordingly not yet possible to say for sure whether fusion research is still more a matter of fundamental research or has progressed to the stage of developing an energy technology.

Over the almost 50-year history of fusion research, the difficulties in developing a fusion power plant have been repeatedly underestimated, with the result that the horizon for implementation had to be pushed further and further into the future, becoming in effect a 'moving target'. Around 1960, for example, it was predicted that fusion technology would be introduced 'within the next decade or two', and as recently as 1990 the US Department of Energy set 2025 as the target for commercial electricity generation.

Fusion experiments are becoming larger and larger in scale, with a high degree of technical complexity, giving rise to considerable financial investment. The planned experimental reactor ITER[1] is the largest research project in the world after the ISS international space station. It is

[1] ITER (International Thermonuclear Experimental Reactor) is used here and throughout the document to mean the rescaled ITER-FEAT project.

scarcely possible that a single country could provide the funds required for this, and so fusion research has been the result of particularly intensive international cooperation. There is a need for a definite political decision to be taken on the mammoth international ITER project, especially as regards the actual figure to be put on fusion research in the 6^{th} framework programme of the EU.

Seen against this background, the German Bundestag's Committee on Education, Research and Technology Assessment has, at the request of the Bündnis 90/Green party group, tasked the TAB (the Technical Assessment Office of the German Bundestag) with drawing up a status report on the topic of nuclear fusion. This is to consider the current state and foreseeable development of nuclear fusion as a future energy source and associated questions in a simple, readily understandable form.

So that this objective could be achieved, given the relatively complex scientific/technical subject matter, this report is broken down into specific, simple topics – such as 'What is nuclear fusion?', 'What is the cost of fusion research?', 'Do we need nuclear fusion?', and so on.

To answer these questions, two challenges have primarily to be faced. On the one hand, the very long time scale of 50 years means that extrapolations going well beyond our recognised level of knowledge have to be made. The uncertainties bound up with these will be expressly pointed out at the appropriate points in order to avoid suggesting any reliability to the forecasts, which cannot be achieved with a 50-year time frame.

On the other hand, the vast majority of the publications on the subject are by experts from the community of fusion researchers, who support the promotion of nuclear fusion. It is extremely hard, in the area of nuclear fusion research, to find any 'independent' experts who have the knowledge to consider the data and methods used from a discerning and critical perspective. The methodology adopted was therefore to interview as broad a spectrum of supporters and critics as possible so that the central lines of argument could be included from both sides. As well as this, the parliamentary hearing on nuclear fusion, which was held on 28 March 2001, has been assessed in depth.

Because there is an immediate need to take a decision on ITER, only fusion using magnetic confinement will be discussed in detail below. This pragmatic approach should not, however, be taken to imply any assessment of the chances of implementing alternative concepts, such as inertial confinement. More detailed information on fusion by inertial confinement can be found in the expert opinion 'Kernfusion' from Basler & Hofmann AG, Zurich (Basler & Hofmann 2001), which was drawn up at the request of the German Bundestag for the TAB.

The present report is greatly indebted to that expert opinion. At this point, we would like to express our grateful thanks once again to the authors of the expert opinion, Dr A. Eckhardt and Mr P. Meyer, for their assistance.

II. What is nuclear fusion?

Nuclear fusion is the process used by the stars, such as our own Sun, to release energy. Our fundamental understanding of nuclear physics tells us that energy can be obtained both by splitting the nucleus of a heavy atom such as uranium (fission) and by merging two light nuclei, such as hydrogen (fusion).

However, before light nuclei can fuse, the repelling forces between them has to be overcome. This happens only at extremely high temperatures, in the region of a few hundred million degrees Celsius. Under these conditions, what is known as a **plasma** is created, that is to say the nuclei and electrons of an atom move independently of one another. Plasma is also regarded as the fourth state of matter (alongside solid, liquid and gas).

In order to obtain enough individual fusion reactions to generate energy technologically, the plasma must be confined for a sufficiently long **time** at sufficient **density** and **temperature**. The **triple product** of density, confinement period and temperature is an important factor for energy production from fusion in a plasma. Achieving this confinement is not a simple matter, since any structural materials coming into unprotected contact with the plasma are rapidly destroyed. Two approaches have been developed to counter this.

Inertial confinement: a tiny ball of fuel, around the size of a pinhead, is heated up and evaporated very rapidly by a strong laser pulse or similar means. Mass inertia prevents the atoms from flying apart immediately. This means that fusion conditions can prevail in the interior of the pellet for an instant before it flies apart. In other words a minute hydrogen bomb is ignited.

Magnetic confinement: the electrically charged particles of the plasma are held together by the action of strong magnetic fields at low density but over periods of a few seconds or more. The magnetic fields are generated by an arrangement of coils through which current flows.

Possible **fuels** for fusion power plants are primarily the two heavy hydrogen isotopes deuterium (^{2}H or D) and tritium (^{3}H or T), as well as helium, boron and various combinations of protons (Liebert 1997). Achieving the reaction conditions for fusion of deuterium and tritium is the most straightforward. This produces a helium nucleus and a high-energy neutron.[2] Deuterium and tritium can be obtained from water and lithium respectively, and are available in large quantities throughout the world.

Another important factor in the operation of fusion reactors is the **amplification factor Q**, which is the ratio of fusion energy to heating energy input. Q=1, where the fusion energy is exactly equal to the energy input, is called **'break-even'**. Since the generation and confinement of the plasma require considerable energy to be input and the conversion of the released heat to electrical

[2] D + T → 4He (3.517 MeV) + n (14.069 MeV)

current is beset by losses, a reactor which is to generate power must have a relatively high Q value.

Future fusion power plants will place the plasma vessel in which the fusion process takes place in the heart of the plant. Magnetic or inertial confinement will prevent the plasma from coming into contact with the inside wall of the vessel, the first wall. In plants for the fusion of tritium and deuterium, the plasma vessel is surrounded by a blanket in which the tritium fuel is obtained from lithium. Production is aided by the neutrons released during the fusion process. The blanket also absorbs the energy generated during nuclear fusion, which is usually converted to electrical power by way of coolants, heat exchangers and generators.

1. Historical background

In 1934, Rutherford was the first to **fuse hydrogen nuclei** in the laboratory **to create helium nuclei**. Fusion research received its first boost when its military potential was recognised. The first **hydrogen bomb** was detonated in 1952, in Eniwetok Atoll in the Pacific.

From **1951** onwards, more attention was paid to the non-military applications of nuclear fusion, in particular the possibility of **power generation**. At this time, 'it was estimated that spending about US$ 1 million over a period of three to four years would be sufficient to learn whether a high-temperature plasma could be confined by a magnetic field' (OTA report, 1987). However, it became evident that this estimate was far too optimistic.

In 1958, military confidentiality was removed from fusion research involving magnetic confinement. This opened the door to more intensive international cooperation. However, in the course of the 'Atoms for Peace' conference and the subsequent euphoria, the difficulties of implementing nuclear fusion were drastically underestimated: 'One report concluded in 1958: with ingenuity, hard work and a sprinkling of good luck, it even seems reasonable to hope that a full-scale power-producing thermonuclear device may be built within the next decade or two' (quoted from OTA 1987).

A group led by the physicists A. Sakharov and I.E. Tamm succeeded, in **1968,** in exceeding the previous best values for the triple product by a factor of 100 using a **toroidal coil arrangement** they called **TOKAMAK**. The tokamak went on to become the internationally leading design concept for fusion reactors. At this time, a demonstration of the technical feasibility of energy generation using fusion was expected within around 10 years (Rowberg 2000). To attain this objective, larger and larger experimental equipment was required. A series of different confinement concepts was investigated in parallel with this. Because of this, and prompted by the oil crisis, the research budget for fusion based on magnetic confinement was substantially increased – in the USA from around US$ 140 million in 1973 to around US$ 810 million in 1977[3] (Rowberg 2000).

In the years that followed, considerable progress was made in research into the basic principles, especially as regards understanding the behaviour of hot plasmas (transport phenomena,

[3] US $ quoted in real terms for the year 2000.

turbulence, etc.) and in the development of technologies for generating and confining hot plasmas (e.g. different configurations of magnetic fields, methods of heating plasma and diagnostics).

Even so, the **implementation horizon** for the technically possible generation of energy had to be postponed further. In 1990, the US Department of Energy set 2025 as the target year for commercial electricity generation. Five years later, this schedule had to be abandoned, however (Rowberg 2000).

In the **Federal Republic of Germany**, fusion research began immediately after the Second World War at the Max-Planck-Institut für Physik in Göttingen, the seat of learning for the scientific and institutional forerunners of the Max-Planck-Institut für Plasmaphysik, IPP, founded in Garching in 1960.

2. Status of research

Of the two concepts for confinement, magnetic and inertial confinement, **only magnetic confinement will be discussed in detail below**. The reason for this is, first, that a concrete political decision needs to be taken in connection with the large international project known as ITER (International Thermonuclear Experimental Reactor), which is currently at the planning stage. Second, magnetic confinement has as a whole made much more progress than inertial confinement, partly because funding invested in Germany and the EU has been substantially greater for the magnetic confinement approach so far. This is not intended to imply any assessment of whether inertial confinement or magnetic confinement is more suitable for large-scale electricity generation, or which of the two approaches has the better chance of being implemented.

Over the last few decades, a range of major experiments succeeded in advancing the magnetic confinement approach substantially. The **triple product** was successfully **increased by a factor of 10 000 over the last 40 years**. A further factor of around 6 is still needed to reach reactor conditions (Pellat 1999). The plant which is currently the largest and the most powerful, the EU JET project (Joint European Torus), is based in Culham, England. The reaction chamber has a radius of 3 metres and has a magnetic field of up to 4 tesla (Paméla/Solano 2001). In 1997, JET succeeded in generating a fusion output of 16 MW in a pulse lasting around a second, and about 5 MW over 5 seconds.

The fusion research community agrees that this reactor-oriented research programme should be continued and that two intermediate steps, ITER and DEMO (Demonstration Fusion Power Plant), should be used to prepare for the **construction of the first commercial fusion reactor in around 2050**[4].

[4] Quite recently, there has been discussion of the possibility of accelerating this timetable by providing additional funding in the first phase (ITER) so that development can be pushed forward far enough to skip one generation of plant in the second phase and combine DEMO and the prototype commercial reactor (King et al. 2001).

The objective of **ITER** is to demonstrate the **physical feasibility of an energy-generating plasma**. The ITER tokamak will be around twice as large as JET, with a radius of about 6 m. The intention is to confine a burning plasma with a Q factor of about 10 for a period of around 500 s. The technological objective, as regards a possible fusion power plant, is to demonstrate the compatibility of the main components with the thermonuclear plasma operation. A test of the concepts involved in tritium blanket elements is also planned.

ITER is the result of a partnership between the European Union, Japan and Russia. Other countries are also participating through one of these partners, for example Canada through the European Union. The USA, which was originally one of the partners, too, withdrew from the project in 1999, supposedly out of budgetary considerations and as a result of the delays to implementation of the project. Germany initially put forward Greifswald as the site of the ITER plant. Because the project entails costs running into billions for the country where it is sited, however, no applications to host the site were later made. Today, Japan, Canada and France appear to be the candidates most likely to provide the site for the experimental plant.

In parallel with ITER, a special **high-intensity fusion neutron source** needs to be constructed to develop and test low-activation materials. The concept for a plant of this kind, the International Fusion Materials Irradiation Facility, **IFMIF**, has been drawn up under international cooperation and presented to the International Energy Agency, IEA (Bradshaw 2001).

Also in parallel with ITER, the Wendelstein 7-X plant is to be used to further develop the **stellarator** approach. This concept is very promising for continuous operation of a reactor.

The intention of **DEMO** is to demonstrate the **technical feasibility of a fusion power plant** and to generate electricity in a continuous operation for the first time. In contrast to ITER, this means that the equipment required for energy conversion is also part of the project. The plant also has the function of testing how materials and components for possible commercial fusion power plants operate together in long-term tests.

If these large-scale experiments, ITER and DEMO, go well, it is possible that construction of the first commercial fusion power plants could begin in around 2045. In this case the structure of the necessary industrial infrastructure would already have been prompted by the work on DEMO (Bradshaw 2001; Najmabadi et al. 1997).

Table 1: Objectives of ITER and DEMO by comparison with the existing technology in JET

	Year	*Fusion power (MW)*	*Pulse duration (s)*	*Proportion of a self-heating**	*Q factor*
JET	1997	16	~1	0.11	0.62
ITER	~2020	>400	~500	>0.67	>10

DEMO	~2030-2040	~2 000	Almost continuous	>0.85-0.9	>30

* Since the α particles carry around 1/5 of the released energy, the following applies: proportion of α heating=Q/(Q+5).

Source: data from Paméla/Solano 2001

3. Scientific and technical challenges

Before we can attain the objective of a fusion reactor which generates electricity, we have to face a whole host of highly ambitious scientific and technical challenges (Bradshaw 2001; Liebert 2001; Samm 2001; Tran 18 April 2001, expert discussion). There is still a major need for research and development in the following areas.

3.1 Physics of burning plasma

The plasma confined under reactor conditions is subject to turbulent and at times chaotic dynamics. Controlling these dynamics is of crucial importance for the functioning of a reactor, as otherwise there may be frequent instances of **instability and plasma peeling** (disruptions). Peeling results in extremely high loads, which over time can destroy the 'first wall'.

The α particles generated during the fusion reaction cause the plasma to heat up locally and may in some cases trigger instabilities. This makes the confinement of a burning plasma a much greater challenge than that of one that is not burning. Clarification of the role of the α particles created during the fusion reaction and diagnostics, **understanding and control of these instabilities** are among the major objectives of the ITER project. Further development of the technologies for heating the plasma and supplying the fuel is also needed.

3.2 Nuclear fusion technology

Operation of the reactor demands that the plasma is not substantially contaminated, for example by coming into contact with the first wall or by an accumulation of products of the fusion reaction (known as ash). If the reactor is to be functional, it is therefore very important to **remove plasma impurities** using appropriate measures. The components used for this, called divertors, are subject to extremely high loads. Their service life must be maximised, since continually replacing them would result in unacceptable down times. For this purpose, it will also be necessary to **continue development of remote control equipment for replacing components and performing maintenance in the 'hot' region**.

The blanket is also an important aspect of reactor operation. This is a structure surrounding the plasma vessel and fulfilling a number of tasks at the same time: 1. slowing the neutrons resulting from fusion, 2. transmitting the heat produced to the primary cooling circuit, and 3. obtaining tritium fuel from lithium with the aid of the neutrons which are released during fusion. Depending on the progress made by the ITER test programme, it may become necessary to **construct a separate blanket test system** (OTA 1995).

3.3 Optimising magnetic confinement

In the design concept for the **tokamak**, which is currently favoured, an electrical current flowing inside the actual plasma is required to maintain confinement. If this current is generated in a conventional way, i.e. inductively, it limits the duration of discharge. **Plants of this kind can only be driven in pulsed operation**. For this reason, **alternative ways** of creating the **plasma current** and hence enabling continuous instead of pulsed operation are being explored. ITER is intended as one such solution (Vetter 2001). Efficient and continuous plasma current operation is at present one of the central challenges in making the tokamak usable for power generation (Samm 2001).

Another approach is being pursued in the form of the **stellarator**. This concept, which is an alternative to the tokamak, confines the plasma by means of a complex coil geometry, making plasma current unnecessary. The **stellarator is thus inherently better suited to non-pulsed continuous operation**. This concept is to be further developed in the Wendelstein test plant in Greifswald and tested for its suitability as a reactor.

Alongside this, **superconducting magnetic field coils** for use in reactors are being developed. These would considerably reduce the need for energy for the coils. At present, the material input required for the coils of a large reactor is still in excess of the production capacity of the individual countries concerned, which means a cooperative solution has to be sought (OTA 1995).

3.4 Low-activation materials suitable for reactors

The development of special materials, in particular for the first wall, the blanket and structures inside the plant, plays a particular part in the functioning of fusion reactors. A series of **highly demanding requirements, in some cases in conflict with one another** , has to be made of these materials. They must withstand extremely high temperatures and periodic heat loads, they must be resistant to neutrons, they must not be susceptible to erosion as a result of the chemically aggressive plasma, and they must generate as little radioactivity as possible while undergoing intensive irradiation by neutrons. These requirements have not yet been met – let alone all at once.

One of the factors affecting the development of low-activation materials of this kind is the extent to which radioactive waste is produced, as this would have to be transferred to a disposal facility.

4. Technical feasibility of fusion power plants

The community of fusion researchers is firmly convinced that the challenges outlined above can be met and that the technical feasibility of electricity generation through nuclear fusion can be demonstrated. The research and development work required for this will take several decades and demand funding on a large scale. **Hence, the horizon for implementation of 2050 assumes not only that scientific and technical development will be successful but also that the economic and political conditions will be favourable.**

All forecasts of this kind are based on the extrapolation of experience to date. However, particularly in research, forecasts over a timescale of this magnitude cannot really be made reliably, because there has to be an unexpected breakthrough. Thus, **over the almost 50 years in which nuclear fusion research has been going on, the difficulties of developing a fusion power plant have been repeatedly underestimated**, with the result that the horizon for implementation had to be pushed further and further into the future.

III. What is the cost of fusion research?

In the past 30 years, substantial public funding has been invested in advancing plasma research. Using today's estimates, **research and development over a further 50 years at a total cost of around € 60 – 80 billion** – of which € 20 – 30 billion would come from the EU – must be conducted before there is a chance of bringing about electricity generation from nuclear fusion (Bradshaw 2001; Liebert 1997).

To assess the question of what contribution to securing a power supply in the long term can be made by this, we need to take a look at the funding of energy research as a whole. If fusion research funds are to compete with funding for the development of new technologies for saving energy and for the use of renewable resources, the judgment will have to made differently from a situation where this money represents additional funds.

1. Research funding worldwide

The money spent by all the OECD countries on fusion research was around € 30 billion over the period from 1974 to 1998 (Bradshaw 2001). Annual investment in civilian nuclear fusion research is currently around € 1.4 billion (Edwards 2000). Substantial research programmes exist, chiefly in the USA, Japan and Europe. In the US, the Department of Energy, DOE, has put in a request for US$ 248.5 million for scientific investigation into nuclear fusion for the year 2001. This includes around US$ 17.5 million for scientific research into inertial confinement fusion using heavy ions, and substantial funds from the defence budget are also allocated to this.

1.1 European Union

In the European Union, almost € 10 billion was spent on fusion research up to the end of the 1990s (Liebert 1999). On average, the annual spend was around € 470 million between 1995 and 1999 (Randl 2001). These costs are divided between around 40% from the European framework programme – in this case EURATOM – and around 60% from direct national funding (Samm 2001). The 5th framework programme provides for € 788 million for fusion research for the period from 1999 to 2002, which is equivalent to around € 200 million annually. For the 6th framework programme, which will last from 2002 to 2006, the European Commission estimates a figure of € 700 million (European Commission 2001)[5].

By way of comparison, in budget year 2001/2002, the European Commission is supporting research and development work from European businesses working in the area of non-nuclear energy to a level of around € 560 million (IWR 2001).

About half the funds awarded by the European Union go to the associated partners, which in

[5] The European Parliament proposed € 800 million. A revised proposal from the Commission provides for € 750 million for the period 2003-2006, of which € 200 million is for ITER (European Commission 2002). The decision-making process is currently under way, so the budgets may yet change.

Germany are the Max-Planck-Institut für Plasmaphysik and the Forschungszentrum Jülich and Forschungszentrum Karlsruhe. The other monies benefit, among other things, the Community projects JET and ITER (Randl 2001).

Table 2: Distribution of research funds between magnetic confinement and inertial confinement in the European Union and the USA as estimated rounded values

Region	Type of confinement	Research funding (€ m in 2001)	
European Union	Magnetic confinement	500	
	Inertial confinement	civilian 5	
		military	not known
USA	Magnetic confinement	250	
	Inertial confinement	civilian 20	
		military	500

Source: Basler & Hofmann 2001, p. 64

1.2 Germany

The contributions made by Germany to the European institutions and hence also to EURATOM are currently, based on the German proportion of the gross domestic product of the EU, 26% or € 48 million. However, Germany is the beneficiary of over 40% of the funds awarded by EURATOM to its associated partners for fusion research, which in 1999 was also around € 48 million (Bradshaw 2001; Randl 2001).

At present, research investment in nuclear fusion in Germany totals approximately € 160 million (Samm 2001; Randl 2001), drawn from funds from Federal level and from the individual German *Länder* and EURATOM.

Tab. 3: Federal spending on fusion research

Year	*Federal funds, rounded to € m*
1995	105
1996	99
1997	108
1998	122
1999	132
2000	135
2001 (planned)	116
2002 (planned)	113

Other research monies are provided by the German Länder. For example, the Max-Planck-Institut für Plasmaphysik is jointly financed by Bavaria, Mecklenburg-West Pomerania and Berlin.
Source: German Ministry for Education and Research 2002

By way of comparison, German Federal R&D spending on renewable energy and efficient use of energy amounted to € 153 million in 2000, and the budget planned for 2001 was € 192 million (German Ministry for Education and Research 2002, p. 250 f.).

Future costs: should ITER be implemented, the distribution of costs remains open to negotiation. If it is sited outside Europe, in Japan for example, the European budget for fusion will probably remain constant, because the host country is to take on a substantial proportion of the construction costs. If a site in Europe is selected, this decision would necessitate considerable cost savings in other areas of the European fusion programme and in all probability an increase to the overall budget as well. However, the community of fusion researchers has predicted that any need to bolster the budget should prove to be limited (Bradshaw 2001).

2. Investment in research plants

The construction budget for the **ITER** project was revised in the period between 1998 and 2000 from an initial € 7 billion to **€ 3.5 billion** (Edwards 2000), which is planned to be spread over ten years. The associated costs of research and development work specifically associated with ITER are estimated at € 700 million, with operating costs at € 240 million per year. Germany is involved only indirectly with the financing of ITER, through its contribution to the EU budget (Bradshaw 2001). Up until now, around € 1 billion has been spent on ITER – mainly for the construction of prototype components (Bradshaw et al. 15 June 2001, expert discussion).

Investment in the **Wendelstein 7-X** experimental stellerator plant **in Greifswald** is estimated at **approx. € 620 million**, which is to be borne 27% by the European Union, 57% by the German Federal authorities and 16% by the individual States German Länder (Randl 2001).

Investment in the **IFMIF neutron source** (International Fusion Materials Irradiation Facility), which is a necessary prerequisite for DEMO, is estimated at **approx. € 600 million**. There will additionally be operating costs, as in the cases of ITER and DEMO (Bradshaw 2001).

The investment for **DEMO** should be **approx. € 8 billion** for an electrical output of 1000 MW. The operating costs for DEMO may be at least partly covered by the electrical power it generates. One decisive factor for the cost levels of DEMO will be whether the project is run as an international cooperative effort or competitively. At least following on from DEMO, it appears possible that the countries which were up until then partners will go their separate ways to ensure that their own national industries benefit from the sites (Bradshaw 2001).

IV. Do we need nuclear fusion?

The question of the future role of nuclear fusion in a sustainable power supply system can only be concretely discussed while considering certain objectives within energy policy, such as:

- Do we need nuclear fusion to cover the globally increasing demand for energy?
- Do we need nuclear fusion as a complementary source, to enable available fossil fuel resources to be used in a sustainable way[6]?
- Do we need nuclear fusion in the energy mix to reduce CO_2 emissions in electricity generation?

The starting point for the considerations below is the widely quoted **thesis**, which refers to technical feasibility but is as yet unproven: **'From the middle of the 21st century fusion power plants will be commercially available.'** Possible developments in energy consumption, both globally and nationally, and the fuels involved will be discussed using available energy scenarios, as will the topics of nuclear fusion and climate protection.

1. Long-term changes in the energy situation

Taking the thesis quoted above, the energy situation from around 2050 onwards becomes significant when attempting to establish the need for nuclear fusion. This necessitates an estimate of the energy situation taking into account the way global demand for energy, established and new technologies, the conditions in which energy policy finds itself and new knowledge about the finite reserves of fossil fuels and the amount to which the atmosphere can be polluted will change over a timescale of at least 50 years. An assessment of this kind can only be made in a relatively vague way today, making various assumptions. Energy scenarios presented in the literature form a starting point for these considerations.

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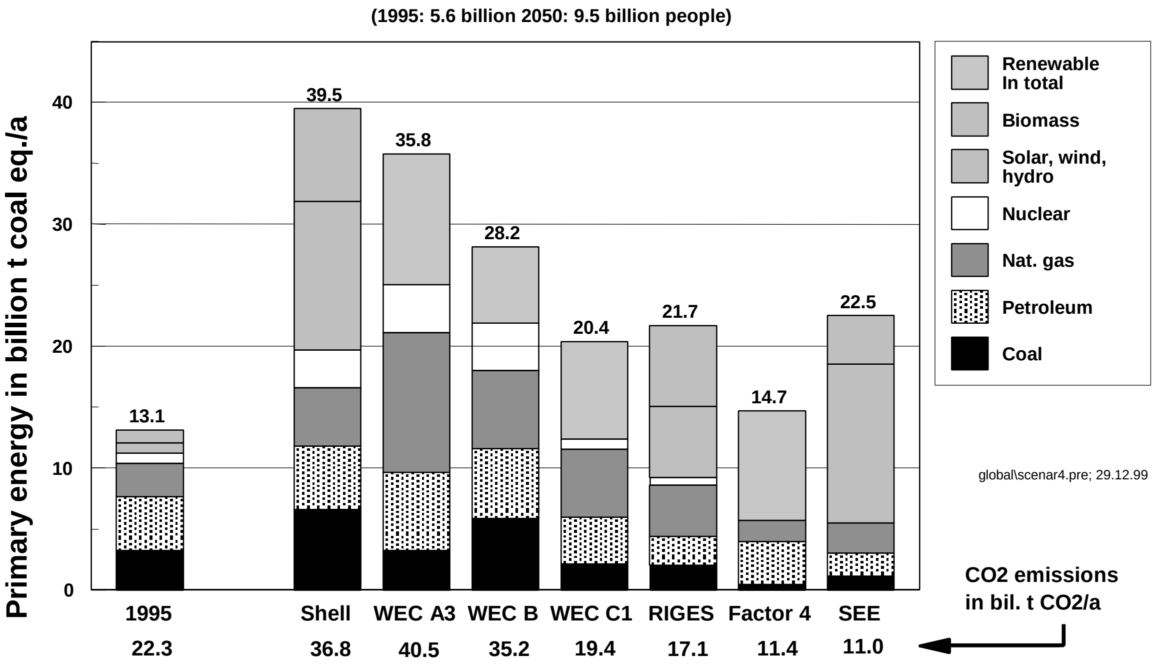
6 The concept of sustainability is understood here in the definition used by the inquiry 'Schutz des Menschen und der Umwelt' appointed by the 13th German Bundestag and 'Nachhaltige Energieversorgung unter den Bedingungen der Globalisierung und der Liberalisierung' appointed by the 14th German Bundestag. There, with regard to the use of fossil fuels, it is stated (1998 inquiry, pp. 25-28 ff.; 2001 inquiry, p. 27): 'Non-renewable resources should only be used where a physically and functionally equivalent substitute is created in the form of renewable resources or where there is higher productivity for the renewable and non-renewable resources.' Cf. also Jörissen et al. 1999, p. 69 f.: 'The supply of proven non-renewable resources must be maintained over time.'

1.1 Long-term scenarios on changes in the demand for energy and the fuels used

1.1.1 Energy demand

Scenarios for world energy consumption, in some cases differentiated by fuel and region, have been published by, among others, the International Energy Agency (IEA), the World Energy Council (WEC) and the European Commission. **Examples of energy scenarios** (Fig. 1) include the Shell scenario (Fig. 2) (Shell 1995), which describes possible global development up until 2060, and the scenarios for long-term development of energy needs from WEC/IIASA (1998), with three different scenarios to 2050 (base year for the forecast 2020) and development trends until 2100.

*Fig. 1: Current scenarios for world energy consumption in the year 2050**

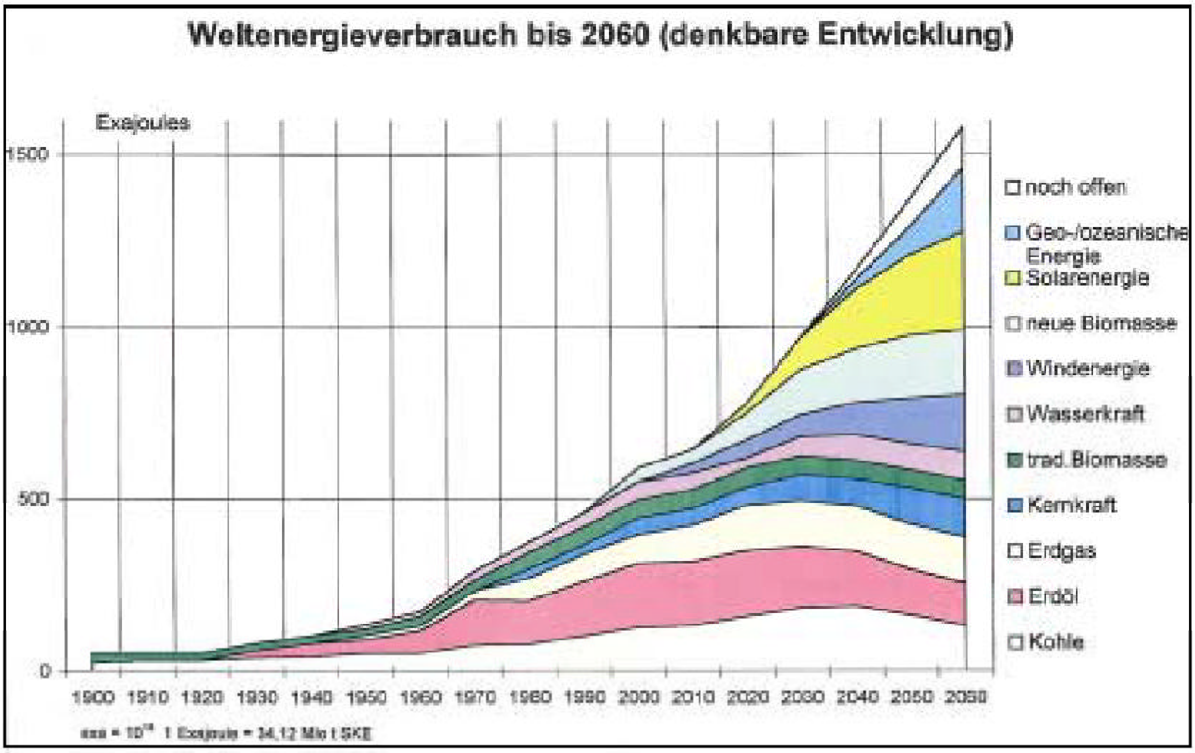


* Population in 2050: 9.5 billion; Shell = 'Sustainable development' scenario (Shell 1995); WEC = various scenarios from world energy conferences in 1995 and 1998 (WEC 1995 & 1998); RIGES = 'Renewable Intensive Global Energy Scenario' (Johansson 1993); Factor 4 = Scenario from Lovins/Hennicke (1999); SEE = 'Solar Energy Economy' scenario (Nitsch 1999); 1 billion t coal equivalent/a = 29.3 EJ/a

Source: Nitsch/Rösch 2001

Among those energy scenarios which are explicitly designed for specific targets, such as a significant reduction in greenhouse gas emissions and/or opting out of the use of nuclear energy, are the global Factor 4 scenario from Lovins/Hennicke (1999) and, for Germany, the long-term solar power scenario from Langniß et al. (1997) and Nitsch et al. (2000). For these, findings include the following: **the further away the forecast horizon** from today's perspective, **the less specific the interpretations of statements which can be derived from it** . For example, the world energy scenarios to 2030 and 2050 investigated in Lovins/Hennicke (1999) show energy consumption figures differing by a factor of seven with similar assumptions about the growth in the economy and the population levels.

Fig. 2: Shell scenario for the development of world energy consumption to 2060



Source: Shell 1998

Comparing the different global energy scenarios, it is evident that the assumption is made that in future there will continue to be a **greater demand for energy**. The global increase in energy consumption for 2050 is essentially an approximation based on the per capita consumption of energy. The **per capita consumption of energy** in industrialised countries is currently about eight times that in less developed areas (Cole 1999). Various expert estimates (from WEC, IEA, EIA etc.) make the assumption that **the global demand for primary energy will increase by a factor of two or three on 1990 levels by 2050**. At the same time, world energy consumption will in future be dominated by the developing countries of Asia. Major influencing factors will be the growth in the global population from what is at present 6 billion people to around 10 billion in 2050, and the considerable need to catch up by economies of the newly industrialised and developing countries.

Although the assumption is made that the energy markets of industrialised countries will stagnate or even shrink, it is here that there is significant **potential for energy savings**[7]. A whole range of obstacles, and the fact that the market has not yet fully matured, counter the exploitation of this potential in the industrialised countries in all sectors of consumption, however.

[7] For example, various scenarios include calculations of a decrease in the overall power consumption in Germany of between 10% and 30% by comparison with current levels by the year 2020 (TAB 2000).

In 1990, around 30% of the primary fuels used worldwide went towards the generation of electricity. The proportions of electricity and heat in energy consumption are going to change, however. **By 2050**, and seen in **percentage** terms, **worldwide** we can reckon on an **increased proportion of electricity as the primary source of power consumption** over current levels. If the total energy consumption doubles, this could approximately treble the demand for electricity (Hogan/Bertel 1995; Holdren et al. 1995).

1.1.2 Fuels

Comparing the global energy scenarios to 2050 (Fig. 1) for the assumed distribution of fuels shows that

- **renewable resources** undergo a considerable increase in all scenarios,
- scenarios assuming broadly unchanged values (such as Shell and WEC A3 and B) simultaneously show an increase in the demand both for renewable resources and for **fossil fuels** and **nuclear power** (overall, this increases greenhouse gas emissions),
- only in those scenarios assuming a significant growth in renewable fuels combined with **more efficient use of energy** and hence a reduction in absolute terms in energy consumption in industrial countries (such as WEC C1, RIGES, Factor 4, SEE) are possibilities of substantial reductions in the consumption of finite energy resources and hence greenhouse gas emissions indicated (Nitsch 2001),
- some scenarios include a blank area for **new ways of producing energy** (e.g. Shell 1995) (Fig. 2) and
- the **nuclear fusion option** does not appear as a separate source of energy in the aggregated illustrations.

Currently, world demand for energy is met largely by **fossil fuels** (see the first column of Fig. 1). The proportion of renewable energy sources is comparatively small at the moment. Forecasts of the future proportion of non-renewable primary fuels in worldwide energy provision fluctuate between 25% and 75%[8] (Basler & Hofmann 2001).

When **assessing** how long into the future **fossil fuels** will last, a decisive part is played by the estimates we can make, given current levels of knowledge, of their static and dynamic **reserves** and the **distribution of the resources and reserves of raw materials**. An overview of the data available and possible conclusions about the expected periods covered by reserves of petroleum and natural gas can be found among others in TAB (2000). The distribution of raw materials is markedly different from one part of the world to another. Germany is also highly dependent on imports of fossil fuels: as far as the current **energy mix** is concerned, the distribution of its imports is spread over more than 15 countries and its own distribution network has sufficient diversity of power supply from a national point of view. However, from a global perspective, the inequality in the regional distribution of 'sensitive' energy reserves (petroleum and natural gas) will in future also correspond less and less to the regional distribution of energy consumption and the growth

[8] Besides these, there are also energy scenarios which assume that there is a possibility of 100% provision by renewable fuels in Europe (LTI 1998).

in this consumption. This means, among other things, that **there will be a marked increase in dependence on imports**.

As far as a sustainable energy supply is concerned, the **assessment of potential for renewable resources**[9] in different energy scenarios plays a decisive part. In contrast to fossil fuels, the theoretical potential for renewable resources is large enough even though the utilisation of these has not yet reached a comparable level of maturity in its technology to that of fossil fuels. This means that specific scenarios for developing the use of renewable resources by around the year 2010[10] are accompanied by numerous assumptions about their technical and economic viability. Scenarios going beyond this (Fig. 1), to about 2050, show major differences in the proportions of renewable resources in the energy supply, depending on the degree of development and the energy saving potential used as a basis. The individual renewable resources (hydroelectric power, biomass power, wind power, etc.) also have **different potentials for development**. The individual scenarios assume an electricity supply based at least to a substantial amount on renewable resources, supposing it to be technically feasible by 2050. The technical feasibility currently runs up against economic limits set, among other things, by the possibilities of adequately storing electricity and the amounts of money needing to be spent on this. The question of the extent to which these limits will be pushed forward by new developments by 2050 remains open.

1.1.3 Energy technologies

The energy scenarios make no differentiation between the technologies that will be used in 2050. They are, however, implicitly determined by certain assumptions about the technologies used. A trend towards a marked increase in the efficiency of energy transformation and storage systems and in energy management is assumed. The rate of technological development is supposed to increase. However, **which energy transformation technology**, such as fuel cells, hydrogen technologies or nuclear fusion, **will play a dominant role by the middle of the 21st century cannot be deduced from the energy scenarios available**.

We also have to consider that the increased use of individual technologies may bring about marked shifts in the use of fuels (for example, competition in the use of natural gas from fuel cells and vehicles powered by natural gas). Probably, energy transformation technologies of this kind have a better (market) opportunity of being operated with various different fuels.

Although it is possible that the anticipated marked increase in the global demand for energy may be slowed by **energy saving measures** – in the form of a mixture of technical measures and changes in behaviour – energy saving measures will primarily take effect in industrialised countries which are already developed and have the appropriate expertise and capital. In the developing countries, measures of this kind will take effect only over much longer periods.

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9 A discussion of individual renewable and 'sensitive' non-renewable fuels can be found in TAB 2000 and Basler & Hofmann 2001.

10 For example, the EU takes 22% as a reference value for the proportion of electricity from renewable energy sources in the gross consumption of energy by 2010, and the national guideline target for Germany is 12.5% (EU 2001).

Currently, there is no sign of any **clear line of technical development** to show which energy transformation technology or technologies will play a dominant role in the middle of the 21st century. Various options appear possible at present: examples are the more environmentally sound use of fossil fuels or the technologies, closer to implementation in practice, for the use of renewable resources. **Here, nuclear fusion is only one of numerous options for future energy provision**.

1.1.4 The context of the energy economy

At present, the energy economy is characterised by a **liberalisation** of the markets for electricity and natural gas, both within the European Union and throughout the world. **Large power plants** are tending to **lose their significance**. At the same time, the **trend** towards **smaller energy transformation plants**, installed close to the consumer and indeed outside the conurbations, is increasing. This is also seen in the parallel provision of electricity and heat in combined heat and power installations, for example in large-scale power stations with correspondingly high utilisation rates. Small plants, both those using fossil fuels and those with renewable fuels, can in principle be linked together using modern I&C technologies to form **virtual power plants**, in order to balance out peaks in load by means of differentiated energy management.

One result of **liberalising the electricity markets** at present is to favour energy transformation technologies which do not demand high levels of investment and which have relatively low operating costs. Currently, these are natural gas power plants. To what extent alternative energy transformation technologies which have less impact on the environment will be successful in entering the market at low cost in future depends on the one hand on the exploitation of their potential for reducing costs and on the other hand on the conditions imposed by environmental and energy policies. A decisive point in the further pursuit of the **nuclear fusion option** is not whether it has massive quantitative potential to generate energy but rather **the strategy selected for energy provision in 2050**[11].

Fusion power plants are suited to a context of **well-developed electricity supply networks**. The easiest power plants to integrate into an infrastructure of this kind are the large-scale base load supply plants. A well-developed electricity distribution network will also be required in future, for example for differentiated energy management to balance out fluctuations in demand between fuels. On the other hand, the increase in decentralised small plants is likely to bring about a reduction in the extent of the power supply network in industrial countries. The industrial countries already have permanent supply structures for electricity which undergo changes only relatively slowly. In the newly industrialised and developing countries, by contrast, change will be much more rapid because of the anticipated growth in energy use.

[11] Current energy policy in Germany is based heavily on phasing out the use of nuclear energy and establishing greater reliance on renewable energy sources (e.g. the Act on the structured phase-out of the utilisation of nuclear energy for the commercial generation of electricity, Bundestag document 14/6890; and the Renewable Energy Resources Act, Bundestag document 14/2341).

1.2 Nuclear fusion option

Nuclear fusion power plants are suited to the **provision of base load electricity** in highly urbanised areas with a well-developed infrastructure. This means that using nuclear fusion gives the additional possibility of generating base load electricity, which will continue to be needed. Taking as our starting point the increasing importance of supply to conurbations (because of the anticipated worldwide growth in the population), fusion plants could supply these conurbations with electricity (sited close to consumers) while other fuels such as renewable ones took a more prominent position in supplying regions of low population density (Vetter 2001).

Seen from today's standpoint, nuclear fusion is a relatively expensive energy source requiring considerable investment (Section VI). The economic starting point for fusion power plants would only change over the long term if fossil fuels became scarce and hence significantly more expensive. In this case, **nuclear fusion** comes into question primarily as **a supply option for the long-term future** in which the reserves and resources of fossil fuels are largely exhausted.

Furthermore, the use of nuclear fusion could have the effect of **protecting other fuels or allowing them to be used in other ways**. For example, instead of using fossil fuels and biomass power for power generation, use could instead be made of their other qualities, such as in the chemical industry.

1.2.1 Nuclear fission and nuclear fusion

From a technical point of view, nuclear fission power plants represent a **possible alternative** to fusion power plants. With the same level of nuclear power utilisation and an acceptance of rising raw materials prices, the supply of uranium is expected to last well beyond the 21^{st} century (Basler & Hofmann 2001). Unlike fusion technology, experience can be drawn from existing plants. Some of the advanced concepts for fission power plants, for example for a helium-cooled high temperature reactor, display good properties from the point of view of safety (Lako 1999). Should a requirement for nuclear power systems arise in future, however, fusion plants have the potential for significant advantages over other well-advanced nuclear systems where safety and environmental protection are concerned (Liebert 2001). In many industrialised countries, nuclear fission has **low acceptance levels** today.

1.2.2 Renewable fuels and nuclear fusion

Renewable fuels and nuclear fusion are often discussed as though they will be in **competition** with one another to a certain extent by 2050. A common feature of both options is CO_2-free transformation of energy and their classification as 'future technologies', making them in principle components in an energy supply independent of fossil fuels. When comparing them, the **level for comparison** used for each is important**:** from the point of view of generating base load electricity, this level for comparison would lie with those renewable fuels which are also suitable for generating base load electricity in relatively large-scale plants (such as geothermal power, hydroelectric power plants, biomass power). In contrast, from the point of view of overall power supply at a national and global level, where aspects such as the security of supply or greenhouse gas emissions have to be considered as a whole from a strategic point of view, our starting point needs to be the total quantity of renewable resources.

Renewable fuels are already used today for electricity generation – with the exception of geothermal power in Germany. This use counters the current trend of the liberalised power market towards small plants. Exceptions are large-scale hydroelectric power plants and off-shore wind farms; at present, the practicable power output of geothermal power plants for the generation of base load electricity in Germany is still an open question. Nuclear fusion plants, by contrast, are exclusively large plants for energy transformation. However, it is also possible to **conceive of the coexistence of both options for energy provision**, for example for reasons of climate protection (Section IV.2) or as a result of striving to provide security of supply through a corresponding diversity of available technologies.

1.2.3 Fossil fuels and nuclear fusion

One fossil fuel which, according to current knowledge, will remain available for a relatively long period and is also used for the base load supply is **coal**. Certain important nations, from the point of view of increasing energy demand, outside Europe, such as China and India[12], are relying on heavier use of this – usually for financial reasons – and are also particularly extending the options for electricity generation from coal. **Fusion power plants would be a good fit with the future infrastructures of supply in these countries,** and could at the same time make a **contribution to the reduction of emissions damaging the climate** (Bradshaw 2001).

As far as the fossil fuels currently used are concerned, competition for use (for instance in the case of **natural gas**) and increasing dependence on imports (for instance in the case of **petroleum**) could result in turning increasingly to them for economic, environmental, social or political reasons, depending on the situation regarding reserves and the political circumstances. In the case of renewable resources, too, necessity might force the use of wind farms at less suitable sites. For the purposes of adequate security of supply, it can therefore be predicted that the use of the widest variety of fuels will be advantageous by 2050 too (Holdren 1995). **Fusion power plants could contribute to an energy mix which can withstand different political and economic developments**.

2. Nuclear fusion and climate protection

Including the nuclear fusion option in a wide-ranging discussion of sustainability (Kopfmüller et al. 2001) is an important part of the question about whether we need it. Climate protection is a politically important aspect which is nonetheless reduced to the environmental side of a sustainable power policy.

During operation, fusion power plants do not emit **any gases which are damaging to the climate**. However, the construction of a fusion power plant in particular requires power for the

[12] India alone will increase its power consumption by a factor of around six in this century; a similar figure applies for China (Bosch/Bradshaw 2001).

manufacture of materials such as concrete. If this energy is provided from fossil fuels, it is associated with the emission of greenhouse gases. If it is based on CO_2-free fuels, the analysis of the life cycle of a fusion power plant appears accordingly advantageous for climate protection (Section VII.2.2). Fusion power plants also contain radioactive material which is associated with emissions in normal operation, a risk of accident and the need to dispose of radioactive waste (Section VII).

The **competitiveness** of electricity from nuclear fusion is **closely linked to the demands of climate protection**, upheld in particular in countries where a certain standard of living has already been attained (Lako 1999). For this reason, nuclear fusion is very frequently classed as an **energy source for developed countries**, for example the current members of the Organisation for Economic Cooperation and Development, OECD. Even if the increasing demand for energy in 2050 can in principle be met by the use of fossil and renewable fuels, the question of the priority of climate protection still remains initially open. We can envisage two directions in which trends could go:

With comparatively **high priority given to environmental and climate protection**, the fusion power plants of 2050 would have to be seen within a context probably characterised by the intensive use of renewable resources. In addition, in this case the overall demand for energy would probably also be smaller. Fluctuations in availability of fuels could be compensated by integrated, differentiated energy management spanning various regions and fuels (Lehman 2001). In addition, it can be predicted that rapidly regulated power plants with a high level of availability would be needed, with the possibility of resorting to hydroelectric power, for example, or to non-renewable fuels. Because fusion power plants are designed for steady and continuous operation, they could not really fulfil this function.

If there were **relatively low priority given to climate and environmental protection**, demand for low-priced (new) energy sources can be predicted to set in in the second half of the 21st century. Although increasing demand for energy would have an advantageous effect on the chances of nuclear fusion being developed, since it is suitable for providing large quantities of additional power, on the other hand by 2050 electricity from nuclear fusion would not be competitive with electricity generated from other base load plants (such as coal-fired or gas-fired power stations), according to our current levels of knowledge[13] (Section VI).

Nuclear fusion represents one **option for reducing greenhouse gases**. Whether nuclear fusion power plants can still make a contribution to climate protection in 2050 depends chiefly on the degree to which ambitious but, seen from a technical point of view, achievable objectives have

[13] This statement is only valid in the absence of energy policy measures on environmental protection (such as taxes on carbon dioxide emissions) which bring with them advantages for energy transformation technologies free of carbon dioxide, such as nuclear fusion.

been met by then, for example in the options of increased use of renewable resources, the increase in energy productivity[14] and the measures taken by consumers[15].

In discussing climate protection, we must distinguish between **tasks immediately before us**, such as the Kyoto protocol and the undertaking by the German Federal government to reduce CO_2 emissions, and **longer-term** ones depending on the extent to which increases in efficiency and the extended use of renewable energy sources and the implementation of energy saving potential are achieved. Because we cannot reckon on the first fusion power plants coming into commission before the middle of the 21st century, nuclear fusion cannot make any contribution to solving current problems of climate protection. Fusion power plants could, however, provide one means of energy provision free of damaging effects on the climate in the second half of the 21st century.

14 Doubling the growth in energy productivity from 1% at present to 2% p.a. is said to be possible and would solve all our energy and emission problems (Hennicke 2001).

15 Even if the vast majority of energy (more than 60%) comes from renewable sources in 2050, the level of CO_2 emissions would double in this period if measures were not taken on the demand side (Hennicke 2001).

V. Is nuclear fusion safe?

Development of fusion technology is guided by recognition of the fact that fusion power plants will only go into operation if strict safety targets are met. A central objective is therefore that fusion power plants should not permit any accidents entailing major risks to the population outside the operating premises or that would give rise to a need for evacuation. To put it another way: **fusion reactors have to be intrinsically safe**.

1. Possible accidents

An important difference between fusion reactors and fission reactors is that uncontrolled nuclear chain reactions are simply not possible in fusion power plants because of their very nature. Even so, the release of only a small fraction of the radioactive material in a fusion power plant could result in a catastrophic accident scenario (Liebert 1999). The quantity of radioactive material is more or less comparable with that in a fission reactor of the same capacity. Almost all of this material is in activated structural materials. However, the tritium is also highly significant, because it is very mobile and hard to control in the event of release. In the form of tritiated water in particular, it may also easily be absorbed into the body.

However, the type of accidents that could occur, how likely these are, and to what extent the radioactive material could then be released, is disputed in the literature (Holdren et al. 1987; Öko-Institut 1995; Raeder et al. 1995). This can be attributed to the fact that assumptions have to be made about the reactor design, since the final design of the first electricity-generating fusion reactors is not yet established. Whether the objective of intrinsic safety mentioned above can be achieved is consequently neither proven nor clearly refuted at present, but **depends on the results of research and development work which has yet to be performed over a period of decades** (Heindler 2001).

2. Violent actions by third parties

In the event of **a fusion power plant being destroyed by an act of war or terrorism** a significant portion of the radioactive and chemically toxic materials would presumably be released. Since almost all of the material is bound up in structural materials, it would depend on the actual scenario of the event what proportion of this was in fact released. If the readily mobile tritium component of a fusion power plant were fully released by some violent event such as a large passenger aeroplane crash or an act of war, the **population over an area of several square kilometres** would have to be **evacuated**. It is assumed that individual doses, even under unfavourable general conditions, could be limited to 250 mSv[16] (Samm 2001). Design concepts up until now have not made any special provision for protection against a violent act of this kind.

3. Proliferation of nuclear weapons

Fusion power plants make a contribution to proliferation if material which can be used directly or after further processing to make nuclear weapons is obtained from them. Acquisition and dealing with key technologies for the development of nuclear weapons also represents a proliferation risk.

In nuclear fusion with magnetic confinement, two factors are specifically relevant to the possibility of proliferation: the **tritium** used as the fuel in the plant, and the possibility of breeding **fissile materials** with the aid of the neutrons generated by the fusion reaction (European Parliament 1999).

3.1 Tritium

Tritium is used in a variety of advanced nuclear weapon designs. It is therefore particularly relevant for vertical proliferation, that is to say the further **development** of the nuclear weapons arsenal. However, it is also relevant to horizontal proliferation, i.e. the **spread** of nuclear weapons. For example, tritium can be used in booster bombs to increase the release of energy from a fission weapon by as much as a factor of ten. This means that smaller quantities of fissile material are needed to make effective nuclear weapons (Liebert 2001). It is, moreover, speculated that boosting might improve the effectiveness of weapons containing reactor plutonium from civilian production (Liebert 2001).

To divert tritium from a fusion power plant, first of all the tritium barriers would have to be opened, which in normal operation would be difficult to achieve (Bradshaw 2001). There must be an increased risk during maintenance and repair work, however. The fabrication and handling of fuel would also be a possible weak point. It is difficult to account for the precise amount of tritium material in a fusion plant. Moreover, a few grams of tritium could easily be transported in portable storage facilities, which are barely detectable by the control techniques we have today. **Tritium accordingly represents a significant proliferation risk in the operation of fusion reactors.**

3.2 Fissile materials

The operation of fusion power plants does not require any fissile material. Fusion power plants produce considerable flows of neutrons, however, which make it possible to breed fissile material. For this, modifications to the plant and especially to the blanket are required and these would be more or less difficult to detect, depending on the design in question. To ensure that no fissile material is produced in fusion power plants, the possibility of the blanket being modified in this way must be prevented (OTA 1987).

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[16] The unit of mSv (millisievert) indicates the radiation energy absorbed by an organism per unit of mass (mJ/kg), taking into account the different effects of different types of radiation (equivalent dose). Natural levels of radiation exposure are around 1 to 5 mSv per annum, depending on the location of home and workplace.

Enabling detection of the introduction of small quantities of breeder material or the removal of small quantities of fissile material from a fusion plant seems feasible (Raeder et al. 1995), since normally there is no such material in a fusion power plant. Various writers have also emphasised that it would be relatively simple to demonstrate the partial use of the neutron flows for the production of weapons material (Liebert et al. 1999). However, if such activities are to be discovered promptly, it will at least be necessary to develop appropriate monitoring systems (Liebert 2001). The **risk of breeding fissile materials which could be used in weapons** is therefore **lower** overall in a purely fusion-driven reactor **than in a fission reactor**.

VI. Is electricity from nuclear fusion economic?

Current forecasts envisage commercial fusion power plants being able to come into operation around the middle of the century. A number of quantitative forecasts of the expected costs of electricity generation in these plants exist (e.g. Delene 1999; Najmabadi 1999; Peterson 1998; Sheffield 2000). To make these forecasts at all, we have to predict for a 50-year timeframe a series of critical and in some cases wildly fluctuating parameters, such as fuel prices, costs of raw materials (lithium and rare metals) and interest rates. These factors have a profound effect on the economic viability, as do, for example, the time it takes to construct a reactor and the procedures for approval and operational monitoring (e.g. safety housings and reserve funds for disposal).

Another factor is that the fusion reactors which may be connected to the grid in 50 years' time will in all probability have very little similarity with the design studies used as a basis today. Taking this as our starting point, viability studies for fusion power plants can at best be used for cost optimisation of the different design options.

Given this situation, assessing the economic viability of electricity from fusion as compared with competing fuels and putting a price on the costs of electricity generation is highly speculative.[17] Even the rate of technological progress and the way costs will turn out in competing energy systems, such as those of renewable resources, which is highly significant for their competitiveness, cannot be predicted in the long term.

What is certain is that **investment will dominate operating costs in the price of generating electricity**. For a plant generating 1 000 MW_e, a figure of € 5 to 6 billion[18] is quoted (Delene 1999). Fusion power plants thus become very capital-intensive large-scale projects. A comparison with other large projects – such as fast breeders – shows that the cost estimates are around the lower limit of what is possible (Ziesing, commissioned by the German Bundestag, 2001). Even the supporters of nuclear fusion technology expect the costs of electricity generation to be higher than those of competing technologies, on the basis of our current knowledge (Delene 1999).

Factors which could shift this relationship in favour of fusion technology are for example a particularly high and consistent requirement for electricity, and high energy prices. These two factors are not mutually independent, however. A long-term rise in energy prices would stimulate the development of technologies and measures for energy savings, and hence have a damping effect on energy consumption.

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[17] A vivid example of how catastrophically wrong long-term forecasts can be is provided by the statement, dating from 1954, made by Lewis L. Strauss, Chairman of the Atomic Energy Commission that in future electricity from nuclear energy would be 'too cheap to meter' (New York Times 1954).

[18] Based on prices in 1999. This is less than the € 8 billion estimated for DEMO, because there is no highly costly analytical and experimental equipment in a power plant, as there is in the case of DEMO.

External costs
Internalising as far as possible the external costs of energy use, for example by giving high priority to climate protection, would be advantageous for the competitiveness of non-fossil fuels. Initial investigations of the external costs of fusion power have shown that material processing and the construction and decommissioning of fusion power plants are much more significant than operation. Seen as a whole, the **external costs** of power generation through nuclear fusion are classified as **comparable** with **wind power, photovoltaic conversion and nuclear fission** , but **much more economical** than electricity generation using **fossil fuels** (Schleisner/Korhonen 1998).

Fusion power from the point of view of energy supply companies
In many respects – an output in the region of 1 000 MW_e, highly capital-intensive projects and the tying up of capital for long periods – future fusion power plants are similar to those using nuclear fission. For this reason, and as mentioned above, they are chiefly suitable for centralised **electricity generation of the base load**.

How great the demand for centralised base load generation will be around the middle of the century is unclear (Section IV). At present, capacity is mainly topped up from smaller units close to the location of the consumer. This **trend towards decentralisation** is bound to gain ground as fuel cell power plants come into the marketplace too. For base load power plants, reliability is a crucial parameter. Frequent and unpredictable interruptions or long down times for maintenance and repair would make fusion power plants unattractive. The assumption made today of an **output availability** figure of 75% for fusion power plants (Bradshaw 2001) is relatively low compared with other large-scale plants, some of which achieve a figure above 95%.

If the present pronounced global trend towards **liberalisation** of the energy markets continues, this high capital burden would be a major disadvantage for fusion power plants, as it must be a drawback to **tie up capital for the long term** in a liberalised environment. An additional factor is that fusion power plants would initially have to compete with reactors which are at least partly amortised and which can therefore produce at marginal cost. Energy supply companies will **only accept fusion power plants if they can expect a clear economic advantage over established technologies**, including a risk premium for the still unknown capability and reliability of a young technology.

It is therefore generally disputed whether DEMO can be followed by fusion power plants capable of economically competitive operation. Initial difficulties could make further government support necessary (Heindler 2001).

VII. Is electricity from nuclear fusion environmentally sound?

A major advantage of power generated by nuclear fusion is that the fusion process **does not generate any climate-damaging greenhouse gases**. A functioning fusion technology would thus be well suited to making a contribution to preventing climate change in the second half of this century. This is discussed in detail in Section IV.2 in connection with the question of demand for fusion power.

Conversely, **radioactive waste** is generated in the operation of fusion power plants. How we evaluate this waste depends on the achievement of ambitious goals in further development of the technology and materials used over the next few decades.

It is likely that societal acceptance of fusion technology will depend to a great extent on appropriate consideration of environmental criteria at the time of deciding between technologies.

1. Radioactivity

In contrast to the case of nuclear fission, the reaction products of deuterium/tritium fusion are not themselves radioactive. Associated with this fact is the hope that it will become possible to construct fusion power plants producing no long-lived high-level radioactive waste which must be kept away from the biosphere over many generations. However, some parts of the plant are exposed to the neutrons which are released during the fusion reaction, and are made radioactive by them. The amount and type of radioactivity this produces depends to a large extent on the choice of materials for these plant parts. The **radioactive waste generated** in the reactors clearly represents the **primary problem associated with radioactivity in nuclear fusion** .

The second key radiological risk is the **tritium** fuel. Due to its specific properties, handling this substance poses certain difficulties. The risks from the activation products and tritium and the emissions during normal operation and on decommissioning will be explained in more detail below.

1.1 Activation products

The inventory of activated material is primarily found in the structures of the first wall, the blanket and the divertors. It is highly dependent on the materials selected. As already mentioned (in Section II.3), a whole range of ambitious demands is made of these materials. Their development is one of the main technological challenges which fusion power must meet in order to succeed. The low level of activation is only one of a number of parameters which have to be optimised in relation to one another but between which certain trade-offs have to be made. The relative importance of the criterion of **preventing long-term radioactive waste** when technical decisions are made about reactor materials is unclear.

For a reference design, the inventory in the SEAFP study is estimated at $1.7 \cdot 10^{20}$ to $1.3 \cdot 10^{21}$ Bq[19] (Raeder et al. 1995; Schaper 1999). By way of comparison, one tonne of uranium has a radioactivity of 10^{10} Bq and the figure for one tonne of fuel rods from reactor operation is 10^{19} Bq (Heinloth 1997). The radioactive inventory of a fission power plant having an electrical output of 1 300 MW will reach a saturation activity of around 10^{20} Bq after about one year of operation (Lederer/Wildberg 1992).

The radiological risk is not only determined by the activity but largely by factors such as mobility, propagation properties and radiotoxicity of the nuclides concerned. Seen in the longer term, the activated structural materials of a fusion power plant are **less relevant from a radiotoxicological point of view than the corresponding materials in a fission reactor** (Liebert et al. 1999).

As regards the overall quantity of radioactive waste produced in the operation and decommissioning of a fusion power plant, a wide range of estimated values exists. In general, estimates reckon on masses of 50 000 to 100 000 tonnes, of which around 25 000 tonnes are from the routine replacement of components such as blanket elements and divertors. If the dwell times of the components close to the plasma should prove to be shorter than anticipated, the amount of waste for disposal would have to be revised upwards accordingly (Liebert et al. 1999). The **quantity** of radioactive waste is thus **comparable with that from a fission power plant** of similar capacity.

According to the recommendations of the International Atomic Energy Agency, IAEA, 30 to 40% of the radioactive waste from a fusion power plant is forecast to be capable of disposal in recycled or conventional form, without restrictions, after a decay time of at most 100 years. The rest of the waste should be used in new fusion power plants or sent for disposal (Bradshaw 2001). The **proportion of waste** which has to be housed in a **geological waste disposal facility** because of its content of long-lived nuclides is in this case **estimated variously as a small amount and up to 30% or more** (Bradshaw 2001; Liebert 2001).

Advanced materials such as vanadium alloys and silicon carbide ceramics would provide the possibility of avoiding long-term radioactive waste to an even greater extent than the currently used high-purity steels, but many years of development work are needed before their usefulness can be proven in practice.

1.2 Tritium

Because of its special properties, **handling tritium makes special demands**. It is a radioactive hydrogen isotope with a half-life of 12.3 years. Its decay products are not radioactive. The β radiation emitted by tritium has a small range, which means that it can be screened even by thin sheets, for example, and does not penetrate the skin. However, absorption into the human body, primarily in the form of water containing tritium which may be swallowed, inhaled or absorbed through skin contact, is hazardous.
Tritium is very mobile and accordingly difficult to control in the event of release. It escapes rapidly through small leaks and – especially at high temperatures – diffuses readily into metal materials

[19] The becquerel unit, or Bq, denotes the number of radioactive reactions per second.

and through metal walls. For this reason, the first wall in a fusion power plant is loaded with tritium. In the case of JET, the development of dust and flakes containing tritium has also been observed (GDCH 2001).

The total tritium inventory of a fusion power plant of 1 000 MW_e using magnetic confinement will be around 2 kg, according to the SEAFP study, corresponding to an activity level of about $7 \cdot 10^{17}$ Bq (Raeder et al. 1995). The plasma and the tritium cycle contain about 10 to 100 g of tritium (Bradshaw 2001). By far the majority of this quantity is within the structural materials of the first wall and in fuel storage containers (Schaper et al. 1999).

The use of tritium in fusion power plants still requires numerous questions to be answered, and technical advances in process engineering are also required. There is a need for development work in the analysis of tritium, for example, and in processes for decontaminating surfaces and cooling water containing tritium.

While we have no **experience of handling** tritium **on a large scale**, any statements on the radiological risks are beset by **major uncertainty** (Heindler 2001).

1.3 Radiological emissions in normal operation and on decommissioning

In normal operation, the **radiological emissions** from a fusion power plant are expected to be **dominated by tritium**. However, activation products, especially those caused by corrosion, may be released into the waste water too (Weisse et al. 2000). Given the current level of development, no precise statements can be made yet about the expected level of emissions from commercial reactors (Vetter 2001).

The assumption that a fusion power plant will **release into the environment at most two grams of tritium per year in normal operation** (IPP 1995) is seriously **disputed by critics** of fusion research. It will probably only be possible to refute these concerns once experiments using realistic amounts of tritium and reactor-specific plant components have been carried out (Liebert et al. 1999).

In the SEAFP study, **a limit of 0.05 mSv/a was set** as a target value for the maximum exposure for **persons in the area surrounding a fusion power plant** . The study came to the conclusion that actual values would probably **fall far below** this limit, including the emissions through the air and by way of waste water (Raeder et al. 1995). The amended version of the German regulations on radiation protection permits public exposure from the targeted use of radioactive substances and ionising radiation to a maximum of 1 mSv per year (previously 1.5 mSv). The natural exposure level for radiation is around 1 to 5 mSv per year, depending on the location of home and work.

The doses for those working inside the plants will depend heavily on the extent to which activated parts of the plant have to be maintained, repaired or replaced and the extent to which such work can be automated. Predictions of the **anticipated exposure of operating personnel** can only be made to a limited extent without any knowledge of the particular plant design (Raeder et al. 1995). Alongside the conventional study of normal operation and accident conditions, it is possible that a further category of risk has to be considered for tritium, that of briefly increased emissions associated with particular procedures within the plant – such as the replacement of components from the first wall. These emissions also have to be taken into account in the exposure figures for the public in the course of normal operation (Heindler 2001).

2. Consumption of resources

2.1 Fuels

Deuterium and tritium, the latter obtained from lithium, are currently the preferred fuels for fusion and are available worldwide in large quantities.

Deuterium occurs naturally in water in a concentration of 33 g per tonne and can be extracted from sea water by electrolysis, for example. The technologies for this have already been tested on a large scale. The **deuterium content in the oceans** is potentially sufficient to meet the global demand for electricity, at 1995 levels, for a period of **150 billion years** (Ongena/van Oost 2000).

Tritium occurs naturally only in minimal amounts. It is obtained from **lithium** by bombarding it with neutrons, which also generates helium. The energy content of the ores known to occur in the earth's crust is in theory sufficient to meet the global demand for electricity at 1995 levels for **3 000 years**, and that of the lithium content in **sea water** for **60 million years** (Ongena/van Oost 2000). However, lithium is also used as a resource in other fields (Tran 18 April 2001, expert discussion), for example in the manufacture of batteries, catalysts, ceramics and pharmaceuticals, which means that possible **conflicts** could arise in the exclusive **use** of lithium obtained from ores.

It will become necessary to supply tritium from outside sources once a fusion plant comes into operation for the first time and presumably – given the short half life of the tritium generated in the blanket – after a fusion power plant is inoperative for a long period. In reactor operation, the tritium needed is bred in the fusion reactor and extracted from the breeder elements in an on-site reprocessing plant. For fusion experiments such as ITER, tritium is initially available in sufficient quantities, for example as a waste product from the Canadian CANDU fission reactors (Bradshaw 2001).

The **pollution to the environment** caused by **mining the lithium occurring** in the earth's crust and by the use of sea water to obtain fuel is classified as **low** (Bradshaw 2001). The procedure for enriching ^{6}Li obtained from naturally occurring lithium is regarded as straightforward, and has already been tested on an industrial scale (Weisse et al. 2000).

As the density of fusion energy stored in the fuel is very high, hardly any transportation is required (Bradshaw 2001). The quantities of deuterium and lithium required annually for a 1 000 MW_e fusion power plant could be delivered **in a single truck** and are estimated as between about 0.6 (Hogan/Bertel 1995) and three tonnes (Bruhns 2000). This would **not involve transporting any radioactive substances.**

Of the alternative concepts for fuel, only that of $D/^3He$ fusion is associated with major problems of resources. In this case, ^3He, which occurs very rarely on earth, would need to be procured by mining the supplies on the moon (Bradshaw 2001).

2.2 Plant

At present various designs of plant are under discussion: these describe a fusion plant without, however, specifying its properties in any detail. Some investigations give **initial indications of the consumption of resources** by a fusion power plant over its entire lifetime, i.e. including construction, operation and decommissioning.

The total mass included in the construction of a fusion power plant is about twice that in any other power plant of comparable capacity. It makes use of predominantly conventional materials, such as steel and possibly vanadium alloys, copper, ceramic and concrete. Relatively rare substances such as beryllium, lead, niobium and titanium are also used in smaller quantities. Experts among the fusion research community do not anticipate any bottlenecks in the resources needed to construct and operate a fusion power plant even if fusion power were used intensively over a period of centuries (Raeder et al. 1995). Usually, the assumption is made that there will be **large-scale recycling**, especially of the relatively rare materials used in a fusion plant.

An initial analysis of the life cycle was drawn up for the materials used in a fusion plant with a capacity of 1 000 MW of electrical power. It was assumed that steel would be the predominant structural material in the plant core (Schleisner 1998). The study's author came to the conclusion that the energy expended in constructing a fusion power plant would be regained after around six months (energy break-even period). The indirect emissions of air pollutants such as carbon dioxide, sulphur dioxide and nitrogen oxides released over the entire life cycle are about twice those of a fission power plant today, primarily owing to the relatively large mass of concrete in a fusion plant. The use of materials (concrete, steel, etc.) in wind power plants leads to indirect emissions which amount to about three times those of fusion[20] (Bradshaw 2001; Schleisner 1998).

3. Other environmental effects

Of the other environmental effects, only emissions of pollutants and greenhouse gases and the disposal of (non-radioactive) waste will be discussed in more detail below. Other environmental effects such as heat and noise emissions or land use fall into an area already familiar from other large-scale power plants.

3.1 Emissions of pollutants

Various plant designs include the use of **chemically toxic substances** such as lead or beryllium, vanadium, lithium and chromium. Typically, these substances are not present in volatile form and do not come into contact with water, which means that the **emissions** to the environment are expected to remain **low** in normal operation. Measures intended to protect against radiological emissions generally also provide effective protection against chemically toxic emissions (Piet et

[20] The results depend very much on the energy mix used and the measures taken to reduce emissions.

al. 1995). Further studies are needed to determine the risk from chemical toxicity to operating personnel.

3.2 Disposal of non-radioactive waste from fusion plants

Fusion plants will give rise to both conventional solid and liquid waste and also, presumably, solid and liquid waste whose chemical composition requires it to be classified as special waste. The proportion of special waste will vary, as will the proportion of radioactive waste, with the design of the plant. More precise details about quantities and composition are not currently available.

3.3 Disposal of waste using fusion plants

Potentially, the flow of neutrons within fusion power plants can be **used** to **treat long-lived radioactive waste and special chemical waste** and render it harmless (Sheffield et al. 2000). When disposing of radioactive waste, it is primarily the conversion of long-lived radionuclides – which may be from fission reactors or from their applications in medicine, industry and research – to nuclides with shorter half lives or to non-radioactive products which is central. In so doing, efforts should be made to avoid the need to separate isotopes, which is a complex procedure entailing risks to operating personnel and the environment.

VIII. Is nuclear fusion socially sustainable ?

In considering sustainable development, an additional factor will decide whether the option of nuclear fusion should or should not be promoted in addition to environmental acceptability and economics, namely social sustainability (Korff 1992). Because many of the questions bound up with this have already been dealt with in the preceding sections, this one will concentrate primarily on the distribution of scope for action and resources between the various options. **To use the term very generally, sustainable development means creating as much flexibility as possible for future actions.**

Once erected, a fusion power plant will tie up capital and resources for many decades and so represents a commitment to this technology over a long period. Seen in this context, an assessment of whether nuclear fusion can be considered sustainable has to be made very carefully. It should be carried out within the framework of a **wide-ranging social dialogue**.

1. Our legacy to the future

Developing fusion power is the result of the attempt to ensure a supply of energy for the future. Nuclear fusion opens up the possibility of benefiting from a virtually unlimited and universally available fuel and of effectively reducing atmospheric pollution by climate-damaging emissions in the long term. In accordance with the principle of provision, fusion research can thus be regarded as an **insurance policy** against two important and undesirable developments in the future, **scarcity of energy** and **climate change**.

By contrast, some experimental plants for nuclear fusion and fusion power plants generate **radioactive waste**. Disposing of this safely must be ensured over a period of decades and possibly even millennia, and **so limits the freedom of action of future generations**. Thus, fusion power plants do not meet the ethical requirement to develop systems which have as little impact as possible, as would taking measures for saving energy, for example (Hubig 1999).

2. Distribution of resources between options

Even without any dispute over the objective of broad scopes of action for future generations, because of the only limited means available not every option can be prioritised, but only certain key areas. **Questions of distribution relate primarily to a choice between nuclear fusion and renewable energy sources**. According to those who oppose fusion research, the government funding made available to nuclear fusion would be better invested in the development of renewable energy. **Points for** this view include:

- the usability of renewable resources is already proven;
- the technical options in the area of renewable resources are better able to be extended step by step and as they are needed, not least because a range of different renewable energy systems is available;
- renewable energy sources can make a contribution, both now and on a larger scale in the future, to the pressing need to solve the problems associated with climate.

One point against this view is that a broad range of different options for electricity generation (and these may include nuclear fusion) is desirable so that

- future developments may be addressed as flexibly as possible, for example precautions taken in case the global demand for energy grows more sharply than anticipated despite an international policy aimed at efficient use of energy;
- risks of availability and dependence on politics can be avoided, for example when importing electricity from solar power plants in regions with a high proportion of direct sunlight;
- energy supply is made as economic and environmentally sound as possible, for example by supplying energy to conurbations primarily from large, centralised plants and to less densely populated regions from small decentralised plants.

The question of the distribution of resources for the promotion of different fuels is also reflected in nuclear fusion research itself, where the current concentration on a few directions for research increases the chance of rapid utilisation of fusion energy but also results in the development potential for the future being restricted and, in the worst case, may lead down a blind alley.

3. Treating different regions fairly

Critics accuse fusion research and the future utilisation of fusion energy of being tailored to the technological possibilities, infrastructure and social context of the highly developed industrialised countries. They point out that the substantial investments required by a fusion power plant can hardly be committed in less developed countries. Moreover, nuclear fusion is clearly not suitable for the specific needs and possibilities of thinly populated countries or regions with relatively strong and constant sunlight.

These arguments are countered by the point that in the second half of the 21st century there will probably be hardly any 'less developed' countries left (Vetter 2001). Some of the significant nations outside Europe, such as China and India, are currently making use of coal for electricity generation. Fusion power plants would fit well in the future supply infrastructures of these countries and would also contribute to reducing climate-damaging emissions (Bradshaw et al. 15 June 2001, expert discussion). Other experts emphasise the fact that nuclear fusion allows the developed nations to make a contribution to the global power supply of the future. If we were to leave technical advances to Korea, China and India, for example, there would be a loss of credibility for the industrialised countries. Because of their favourable starting point from economic and technical/scientific points of view, these countries should feel particularly under pressure to meet the challenge of making a contribution to solving the world's energy problems (Samm 2001).

4. Avoiding conflict

The development of a virtually inexhaustible source of energy and the universal availability of its fuel means that nuclear fusion is well placed to avoid conflicts over resources. In addition, the strong **international cooperation on fusion research is contributing to international understanding** . However, it is dubious whether the knowledge and resources required to erect and commission fusion power plants will be as universally available as the fuel concerned.

Energy generation through nuclear fusion is associated with a **risk of proliferation**, albeit a limited one, and the development of inertial confinement fusion has synergies with military applications.

There is also a potential for conflict in the lack of acceptance by the public. Energy generation through nuclear fusion will only be accepted if it meets the needs and concerns of society. Important decisions should be made in a context of public dialogue and a democratic process which enables less influential members of society to contribute to the outcome as well.

5. Acceptance

Acceptance is greatly affected by social context. It is not possible to make a forecast today of future levels of acceptance, especially those in 2050 when the first commercial fusion power plants might come into operation. To do so we would need, to take an example, to answer the question of whether our society will be shaped by **individualistic**, **egalitarian** or **hierarchical** forces in 50 years' time. This will have a decisive influence on how fusion technology is perceived and accepted by society (Thompson 1991). A number of favourable and inhibiting factors will be mentioned below.

Factors in favour of good public acceptance of fusion energy are, taking the point of view of fusion researchers, primarily the low level of emissions of greenhouse gases and the low risk of accidents with serious consequences for the environment. Nuclear fusion is claimed to open up the prospect of attaining a high quality of life worldwide without any risk of the problems of distribution of energy or unacceptable changes to the environment (Bradshaw 2001).

By contrast, critics counter that major projects tend to arouse scepticism among the general public. Fusion power plants could also run into problems with public acceptance because they contain a significant quantity of radioactive material and require disposal facilities for radioactive waste.

In many of the industrialised nations, **nuclear fission** is finding **little acceptance** at present, while views on **nuclear fusion are still open**. This puts fusion power plants in a relatively favourable starting position. If public acceptance were to turn in favour of nuclear fission, then there might be competition for fusion power plants from new designs for fission power plants, which have to fulfil similar safety requirements to fusion plants but can build to a greater extent on already tried-and-tested fundamentals.

Nuclear fusion is not currently a hot topic among the public, and general knowledge on the subject is poor (Hörning et al. 1999). All fusion research facilities in Germany pursue active public relations policies. At EU level, initiatives on informing the public are being prepared, and intend to make particular use of the Internet as an information medium (Vetter 2001).

However, in the past **pure information or advertising measures** intended to **promote acceptance** have largely proved **ineffective**. To avoid crises of acceptance and confidence, **early and intensive dialogue with no preconceptions is required between scientists, interest groups and the public**.

IX. What should be done?

Despite the shortfalls in knowledge and the problems of evaluation which have been discussed in detail in the preceding sections, there is no reason to leave development of fusion energy to its own devices. Although many questions cannot be reliably answered at present regarding whether and to what extent fusion energy will respond to the many aspects of the principle of sustainability, it is nonetheless already possible to formulate corresponding requirements and identify the conditions under which fusion development can satisfy these principles. It is then possible to consider the potential for shaping fusion in social terms. What intervention can influence development so that these conditions can be met? Seen in this way, the following general options are open to research policy:

- 'continuation' option
- 'thorough evaluation' option
- 'reorientation' option

The purpose of these options is to open up the whole range of ways politics can shape things. The actual position adopted within this range of possibilities is a matter for political evaluation and decision. These options are presented below. Nonetheless, they should not be regarded as sharply delineated from one another, since mixed versions of these basic options are also conceivable.

1. 'Continuation' option

The 'continuation' option means conducting further intensive research in the existing key areas, primarily **following the ideas of the fusion research community**. This option would allow the **ongoing momentum of this area of research** to set the agenda and continue the previous strategy of research policy in a methodical way.

The continuation of the already proven research policy recognises the outstanding scientific successes of the past in investigating the basic principles of nuclear fusion. An optimistic approach, as regards the forecasts of the horizon for implementing electricity generation through nuclear fusion, would demand a decision in favour of the 'continuation' option. However, this strategy could be justified even with less optimistic estimates if the positive aspects of nuclear fusion research, in particular its significance as a scientific and cultural achievement and its contribution to international understanding, are rated highly. In this case, however, fusion research would compete with other similar research plans such as the ISS international space station and elementary particle research.

Pursuing the 'continuation' option would mean a **clear decision in favour of the ITER project**. This would require an active line to be taken in identifying a site and a clear commitment to sufficient financing guaranteed in the long term for reactor-oriented fusion research in the 6th framework programme and beyond.

An important determinant in the success of this strategy is the provision of a broad consensus on the usefulness of new projects requiring finance and solid support on the political level as a whole. This is highly significant, since our political system does not readily lend itself to determining financial resources for projects which will last for decades.

2. 'Thorough evaluation' option

The 'thorough evaluation' option consists of a comprehensive evaluation of the whole topic surrounding nuclear fusion, **bringing in outside expertise** and using **sustainable energy supply criteria** as a guiding principle. The result might be to **interrupt the existing momentum**.

The strategy follows the realisation that the sequential approach applied hitherto of initially demonstrating the scientific feasibility and then showing the technological possibilities of implementation, and only as the last step investigating the socio-economic feasibility, does not necessarily lead to a sustainable means of energy supply in the future. Rather, the demands made in the shaping of fusion technology which are derived from the model of sustainable energy supply should be taken into account in a holistic way in the technological decisions to be made. This consequently also necessitates the formulation of **reversal or termination criteria** if the 'moving target' phenomenon persists. This is important, because both expertise and infrastructure will be accumulated in the course of spending consistently large amounts on research funding for large-scale fusion projects, and could develop their own momentum, which could hinder or even prevent later reversal.

The consequence for **ITER** would necessarily be to **postpone any decision on further involvement** in the project while evaluation was still going on.

If the evaluation made is positive, there should be no more delay to the implementation of ITER. However, it would be sensible to set up a **continuous monitoring process** which would ensure the reversal and termination criteria were observed. In the event of a negative result, measures would have to be taken to give fusion research a new direction.

3. 'Reorientation' option

This option means bringing the initial approach of **developing nuclear fusion as an energy technology by the tokamak route as quickly as possible to an active close** and going back to a **research programme** with the focus on a broader-based understanding of the **scientific principles** and **alternative approaches to confinement**. This would force **the ongoing momentum of this area of research to be halted**.

The basic idea of this strategy is that it is sensible to postpone investment decisions in major projects until a scientifically founded selection of the reactor development concept which is most promising in the long term can be made. So that the scientific understanding required for this can be gained, existing research plant would have to be used and a whole range of relatively small new plants would have to be funded in parallel with this, so that a targeted research process for testing the different confinement approaches could be initiated.

This entails a considerable restructuring of fusion research, similar to that undertaken around the middle of the 1990s in the USA in the context of budget restrictions, for example (Department of Energy 1999). There, however, it was shown that maintaining a strong, balanced fusion research programme at the same time as undergoing swingeing budget restrictions was a difficult management challenge. There is a risk that valuable expertise is lost and may have to be laboriously built up again later on.

To pursue the 'reorientation' strategy option would be to make a **clear decision against ITER**. Funds which would be freed up by this might be able to be redeployed in other areas of energy research.

However, it remains an open question how a restructuring strategy of this kind can be implemented, given the many international and interwoven factors in fusion research, without bringing into question Germany's reliability as a partner in international cooperative projects.

The central challenge – regardless of which research strategy is to be followed in practice – remains that of **building up independent expertise** and organising broad **social debate**. Given the problem that it is virtually impossible to directly involve society, due to the remoteness in time and lack of any everyday experience of fusion, this is no simple matter.

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Annex

1. Index of tables

2. Index of figures

3. Parliamentary hearing

On 28 March 2001 the Committee on Education, Research and Technology Assessment of the German Bundestag held a hearing on the subject of nuclear fusion. As well as Committee members, the Parliamentary members of the 'Nachhaltige Energieversorgung' inquiry were entitled to ask questions. A record of the hearing was kept in the form of brief minutes (German Bundestag 2001). The following experts were called:

– Prof Alexander M. Bradshaw, Max-Planck-Institut für Plasmaphysik, Garching
– Prof Hardo Bruhns, European Commission, Brussels
– Dr Anne Davies, Department of Energy, Washington D.C.
– Dr James Decker, Department of Energy, Washington D.C.
– Prof Manfred Heindler, Technical University of Graz
– Prof Peter Hennicke, Wuppertal Institut für Klima, Umwelt, Energie GmbH
– Dr Wolfgang Liebert, Interdisziplinäre Arbeitsgruppe Naturwissenschaft, Technik und Sicherheit IANUS, Technical University of Darmstadt
– Harry Lehmann, Wuppertal Institut für Klima, Umwelt, Energie GmbH
– Prof Manfred Popp, Forschungszentrum Karlsruhe
– Prof Ulrich Samm, Forschungszentrum Jülich
– Dr Jörg E. Vetter, Forschungszentrum Karlsruhe
– Dr Joachim Ziesing, German Institute for Economic Research, Berlin

Statements made during the parliamentary hearing are indicated in this report by the name of the originator and the date of the hearing.

4. Expert discussions

In the course of its work for the commissioned expert opinion, Basler & Hofmann conducted a series of additional expert discussions:

– Dr G. Hörning, Centre for Technology Assessment at Swiss Science and Technology Council, on 29 March 2001
– Prof M.Q. Tran, Plasma Physics Research Centre, Ecole Polytechnique Fédérale de Lausanne, on 18 April 2001
– Prof D.H.H. Hoffmann, Gesellschaft für Schwerionenforschung und Institut für Kernphysik, Technical University of Darmstadt, on 23 April 2001
– Dr W. Liebert, Interdisziplinäre Arbeitsgruppe Naturwissenschaft, Technik und Sicherheit, Technical University of Darmstadt, on 7 June 2001

– Prof A.M. Bradshaw, Dr H.W. Bartels, Dr H.-S. Bosch, Dr T. Hamacher, Prof K. Lackner, Max-Planck-Institut für Plasmaphysik, Garching, on 15 June 2001

Statements made during the expert discussions are indicated in this report by the name of the originator and the date of the discussion.

Glossary

Blanket – the part of a fusion power plant surrounding the plasma vessel and in which (1) the fusion neutrons are slowed, (2) the heat generated is fed to the primary cooling circuit and (3) tritium fuel is obtained from lithium with the aid of the neutrons released during the fusion process.

Break-even - the output released in the plasma by the fusion processes is exactly the same size as the heat input from outside, i.e. Q=1 (see Q).

DEMO – large-scale experimental plant planned to follow on from ITER and intended to demonstrate the technical feasibility of a fusion power plant and generate electricity in continuous operation for the first time.

Deuterium – the heavy hydrogen isotope ^2H, a possible fuel for fusion power plants.

Divertor – a measure in the plasma vessel to remove plasma impurities and to dissipate heat in the case of magnetic confinement.

First wall – internal wall of the plasma vessel in which the fusion process takes place.

IEA - International Energy Agency

IFMIF - International Fusion Materials Irradiation Facility. High-intensity neutron source for developing and testing low-activation materials. A plant of this kind was designed under international cooperation and presented to the IEA.

Ignition – the power released by fusion processes to maintain the plasma temperature without having to input heat from outside.

IIASA - International Institute for Applied Systems Analysis

ITER – a large-scale experimental plant for magnetic confinement, planned as a partnership between the European Union, Japan and Russia, in which a deuterium/tritium plasma is to be maintained in a stationary operation with high fusion power.

Lawson parameter – the product of plasma density and confinement time, which with the plasma temperature determines the relationship between energy production through fusion and energy supplied from the outside.

Nuclear fusion – the merging of light atomic nuclei to form heavier ones.

Plasma – a material consisting to a large extent of ionised atoms or molecules and their free electrons.

Proliferation – the passing on of materials, devices and knowledge which make it possible for third parties to obtain nuclear weapons.

Q – defines the relationship between fusion output and the power supplied to the plasma.

SEAFP – Safety and Environmental Assessment of Fusion Power project, part of the 3rd framework programme of the European Union, 1990 to 1994.

SERF - Socio-Economic Research on Fusion, a project initiated by the European Union in 1997.

Stellarator – the toroidal confined shape of the plasma which is obtained from a system of external magnetic coils.

TOKAMAK – toroidal confined shape of the plasma. Externally arranged magnetic coils and an electrical current flowing within the actual plasma produce overlapping magnetic fields.

Triple product – the product of ion density, confinement time and ion temperature. For the plasma to burn by itself, the triple product must attain approximately a value of
10^{22} m^{-3} s·keV.

Tritium – the heavy hydrogen isotope ^3H, a possible fuel for fusion power plants.

WEC - World Energy Council