Contribution to the debate on the Green Paper
Towards a European strategy for the security of energy supply

Name	Fusion Technology Committee (a sub-committee of the main consultative committee for the European fusion programme, CCE-FU)
Organisation	
What are you areas of interest?	Fusion and energy supply
Contact person	Professor Alex Bradshaw (if not available: Dr. Thomas Hamacher)
E-Mail	Alex.Bradshaw@ipp.mpg.de, Thomas.Hamacher@ipp.mpg.de
Telephone	0049 89 3299-1342, 0049 39 3299-1469
Fax	0049 89 3299-1001
Address	Max-Planck-Institut für Plasmaphysik, Boltzmannstr. 2, 85748 Garching bei München, Germany

Please add your answers after the question(s) which deal most closely with the subject(s) on which you wish to comment so that the Commission can deal with the remarks efficiently and swiftly.

1.	Can the European Union accept an increase in its dependence on external energy sources without compromising its security of supply and European competitiveness? For which sources of energy would it be appropriate, if this were the case, to foresee a framework policy for imports? In this context, is it appropriate to favour an economic approach: energy cost; or geopolitical approach: risk of disruption? The commodity energy is of paramount importance for a modern economy and and will become increasingly so in future. This important fact is easily overlooked because energy costs represent only a small fraction of the gross domestic product. Lack of access to sufficient energy - as in the time of the oil shortages in the 1970's – leads immediately, however, to extreme distortions of the market and can result in economic and political crises. It would therefore seem very unwise for the European Union to increase its dependence on external energy sources. The importance of energy as a production factor can be directly inferred from the laws of physics, as pointed by Friedrich Hund (*Die physikalischen Rahmenbedingungen unserers Daseins*, Göttingen, 1976). Energy is the only commodity in our life that is

	irrevocably degraded by its use. In other words, the final result of every energy conversion chain is the production of low-value heat from high-value primary energy. The petrol in a car, for example, produces heat and mechanical energy, which drive the car. The motion of the car is only possible against the various forces of friction. The friction of the tyres on the road and of the car itself in the air leads than to a further "heating" of the environment. The same is true for all uses of electricity in the home: heating, lighting, cooking, washing, etc. Material cycles, on the other hand, can be "closed", but then only by the supply of energy. Materials are always degraded by their use: iron is oxidised, water is polluted, but the fundamental constituents – atoms and molecules – remain. The degradation can be reversed: iron can be reduced, water can be purified or desalinated, but the crucial factor in closing the material cycle is the input (again) of energy.
2.	Does not Europe's increasingly integrated internal market, where decisions taken in one country have on an impact on the others, call for a consistent and co-ordinated policy at Community level? The European fusion programme is an excellent example of a fully integrated research activity co-ordinated by the EU.
3.	Are tax and state aid policies in the energy sector an obstacle to competitiveness in the European Union or not? Given the failure of attempts to harmonise indirect taxation, should not the whole issue of energy taxation be re-examined taking account of energy and environmental objectives? Answer:
4.	In the framework of an ongoing dialogue with producer countries, what should supply and investment promotion agreements contain? Given the importance of a partnership with Russia in particular, how can stable quantities, prices and investments be guaranteed? Answer:
5.	Should more reserves be stockpiled - as already done for oil - and should other energy sources be included, such as gas or coal? Should the Community take on a greater role in stock management and, if so, what should the objectives and modalities be? Does the risk of physical disruption to energy supplies justify more onerous measures for access to resources? Answer:
6.	How can we develop and ensure better operation of energy transport networks in the European Union and neighbouring countries so as to enable the internal market to function properly and guarantee security of supply?

	Answer:
7.	The development of some renewable energy sources calls for major efforts in terms of research and technological development, investment aid and operational aid. Should co-financing of this aid include a contribution from sectors which received substantial initial development aid and which are now highly profitable (gas, oil, nuclear)? Answer:
8.	Seeing that nuclear energy is one of the elements in the debate on tackling climate change and energy autonomy, how can the Community find a solution to the problem of nuclear waste, reinforcing nuclear safety and developing research into reactors of the future, in particular fusion technology ? Advances in plasma physics and fusion technology show that nuclear fusion - the energy source of the sun and the stars - could provide the cornerstone of a future sustainable energy system. Even though its impact on energy supply will only be felt towards the middle of the present century, nuclear fusion in combination with renewable energy forms is potentially the most powerful solution to the long-term problems of climate change and security of energy supply. To answer this question more fully we provide in the following a short description of fusion and its potential role in energy supply. 1. What is nuclear fusion? When the nuclei of deuterium and tritium (isotopes of hydrogen) fuse, a helium ion (or α particle) and a neutron are produced and energy is released. The most promising path to harness energy from fusion reactions under terrestrial conditions is via magnetic confinement: Deuterium and tritium are heated to very high temperatures forming a so-called plasma, in which the nuclei collide frequently and a certain fraction of nuclei undergo a fusion reaction. The temperatures necessary to ignite the plasma are between 100-200 Mio °C. Ignition means that the fusion reactions in the plasma are sustainable without any outside heating, although in practice for a power plant a “burning plasma” with a power amplification factor (Q) of 20 – 40 will be sufficient. Obviously no normal vessel is able to contain a medium with such a high temperature. All the particles in the plasma carry, however, an electrical charge and can thus be confined by a magnetic field. It transpires that a doughnut-shaped configuration of the magnetic field “cage” is appropriate for this purpose, although the story is actually a little more complicated: the magnetic field lines not only have to be doughnut-shaped, they also need to have a helical twist. This scheme is referred to as magnetic confinement. Different proposals have been made to produce helically-wound doughnut-shaped magnetic field cages. The most successful approach has been the tokamak, first realised in Russia. Currently, however, the tokamak can only operate in a pulsed mode. Base-load electricity plants need of course to produce power under steady-state conditions. Much of the current R&D activity is thus directed towards finding steady-state tokamak regimes. In parallel, the stellarator is successfully pursued in several countries,

in particular Germany, Japan and Spain.

2. Status of nuclear fusion and fusion technology

Progress on the path to ignition in magnetic confinement fusion research is best characterised by the improvement in the triple product. The triple product is the product of plasma temperature, plasma density and energy confinement time (the latter is a measure of the heat insulation of the plasma). The figure below depicts the increase in the triple product by five orders of magnitude in the last three decades. Only a factor 5-6 remains to be overcome before ignition is reached. The first promising results were achieved in the Russian tokamak T3, following which tokamaks were constructed in many countries at the beginning of the seventies. Construction of the Joint European Torus (JET) in Culham near Oxford, England started at the end of the seventies. It went into operation in 1983 and remains the largest and most advanced fusion device in the world. The increase in fusion triple product in the last 30 years can be compared with the progress in microelectronics in the same period: the capacity of memory chips has doubled every 15 months (Moore's law).

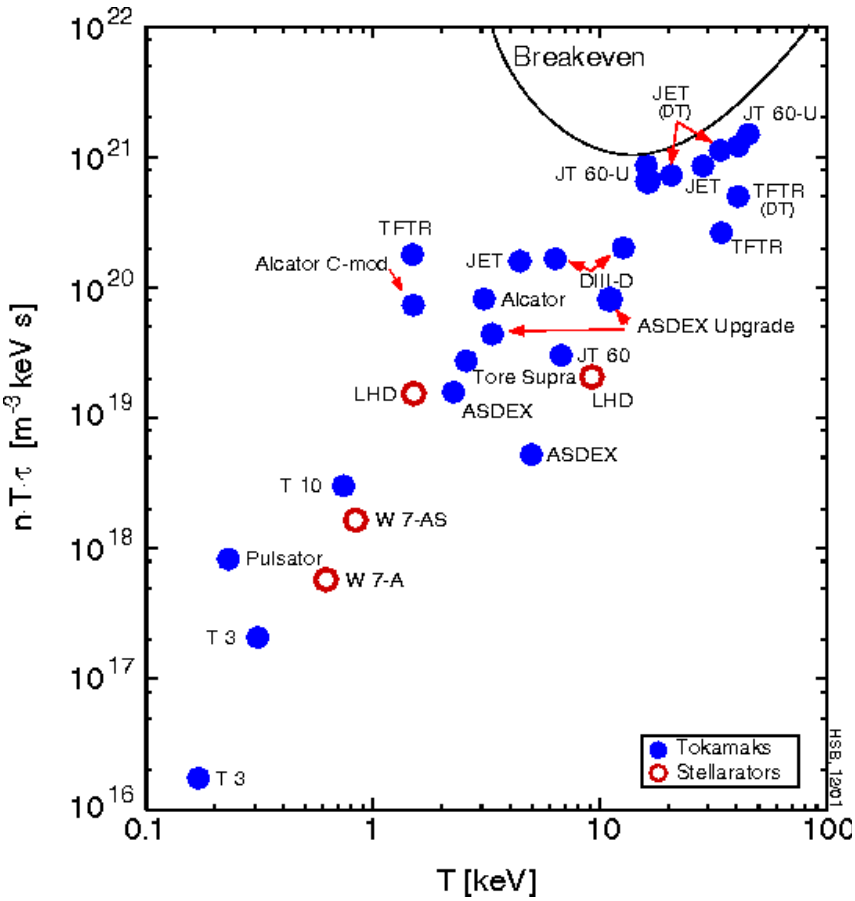

Figure: The development of the triple product of plasma temperature, plasma density and energy confinement time in the last three decades. The temperature 1 keV is equivalent to 11 Mio. °C.

The leading role of Europe in fusion research is, however, not only due to JET, but also to a fully integrated research programme involving all the national facilities in member countries as well as Switzerland. Moreover, the JET experiment, the fusion technology programme and the European contribution to the planning of the international experiment ITER (= International Tokamak Experimental Reactor) are administered by the fusion research facilities in member states (Aassociations) themselves within the framework of the European Fusion Development Agreement (EFDA) The European Research Area in fusion has been reality for several decades!

At JET, experiments with deuterium and tritium have led to considerable power production. 16.1 MW fusion power was produced for about a second and about 4 MW for five seconds. The fusion reaction produced for a short period nearly as much power (65%) as was delivered to the system in the form of external heating (Q = 0.65).

The major physics issues in the world-wide fusion programme are: improvement of the energy confinement time, plasma stability, particle and power exhaust, and α particle (helium nuclei) heating. Although satisfactory solutions to most of the problems have been found in the last twenty years, further research is still required. On the technology side substantial advances in various fields such as superconducting magnets, high heat load materials, materials able to withstand high neutron flux, remote handling devices, plasma heating and diagnostic techniques are necessary. Materials for fusion devices need to fulfil two objectives: (i) they should retain their mechanical properties even after irradiation with intense neutron fluxes and (ii) neutron-induced activation should not lead to the production of long-lived radioactive waste. A number of materials have been identified as candidates for future fusion power plants. Experimental data are unfortunately lacking, since no existing neutron source is able to produce neutron fluxes of the intensity and spectrum expected in fusion plants.

3. The path to nuclear fusion

The European fusion strategy has always been reactor-oriented. Via two major steps (the international ITER experiment and an accompanying programme and, subsequently, the demonstration reactor DEMO) the programme is intended to provide the scientific and technological basis to build and operate economically viable fusion power plants by the middle of the 21st century. The first step has three major parts: construction and operation of ITER, development of fusion technologies including advanced materials and improvement of the magnetic confinement scheme.

ITER (= International Tokamak Experimental Reactor) is intended to demonstrate the viability of a fusion power plant and is a collaboration involving the European Union (and Canada), Japan and the Russian Federation. The first phase of the ITER Engineering Design Activity (EDA) from 1994 to 1998, in which the US was a fourth partner, resulted in a machine which would have reached ignition but would have cost about 6.5 Bio. Euro (capital costs) After the US left the project for political reasons, the design was modified in an extension of the ITER-EDA from 1998 to 2001 to produce a

lower cost, lower performance version. The so-called ITER-FEAT may not reach ignition, but will be characterised by a power amplification factor Q of at least 10. The design modifications still allow the major physics objectives of ITER to be met, but may leave some important technological questions unanswered (see below).

Further improvements of the magnetic confinement scheme are necessary. The pulsed mode of the conventional tokamak is not feasible for a power plant. Two lines of improvements are as follows. The first is called the "advanced tokamak" in which – amongst others - techniques are developed to replace the inductive current drive. Many existing machines have already investigated such scenarios. The second approach is to change (substantially) the magnetic field cage, so that only external magnetic fields are required and an induced plasma current becomes unnecessary, as in the stellarator. Two new stellarator projects are now being pursued: LHD in Japan went into operation in 1998; WENDELSTEIN 7-X in Germany is expected to start operation in 2006. A smaller stellarator is in operation in Spain.

The development of suitable materials for fusion power plants requires the construction of an intense neutron source. A world-wide collaboration under the auspices of the International Energy Agency (IEA) in Paris has been launched to design the International Fusion Material Irradiation Facility (IFMIF). The conceptual design report was produced at the end of 1996.

These activities (ITER, advanced concepts and technological development) will form the basis for DEMO, the detailed design work on which could be started in 2020 after ITER has been operating for about five years.

4. Inherent advantages of nuclear fusion

In recent studies the socio-economic impact as well as the environmental and safety aspects of fusion have been investigated in detail. The main result of all these studies is that fusion fits very well into the concept of a sustainable energy future.

As to the question of external dependence, fusion energy has the inherently attractive feature that the primary fuels needed for fusion (deuterium and lithium) are widespread and abundant, thus increasing the security of energy supply in an uncertain world.

The safety and environmental characteristics have been analysed in a series of reports. Accident analyses have been performed within the framework of system studies and in even more detail for ITER. Although ITER is not in all aspects comparable to a later power plant, it has many similar characteristics. Different methods are applied to arrive at a complete list of forseeable accident scenarios. Reactivity excursions are not possible in a fusion power plant. At any time, the plasma contains a very small amount of fuel so that, in case of a severe accident, the fusion reaction could continue for some 10 seconds only. Hypothetical severe accidents are therefore all related to failures in the cooling system which can be caused either by power failures or ruptures in cooling pipes or both. As an example, a severe accident scenario, a total loss of coolant, is brierfly described: Shortly after the accident the fusion reaction will come to a halt. This

happens because the walls surrounding the plasma are no longer cooled and their temperature increases. Impurities, evaporated from the hot walls, enter the plasma. The larger impurity content in the plasma disturbs its energy balance and more energy is radiated, thus cooling down the plasma. The fusion reaction is extinguished. With no more fusion reactions, only the decay of the activation products in the structural materials and the blanket produces heat. Detailed calculations show that the heat produced will be dissipated by radiation to the inner walls of the cryostat. Temperatures in the structural materials will stay well below the melting temperature and keep the confinement barriers intact.

As a worst case scenario it was assumed that the vulnerable tritium inventory of the fusion plant (roughly 1 kg) is released at ground level. Such an accident could only be initiated by a highly energetic external event such as an aeroplane crash on the plant. Even if the worst weather conditions are assumed, only a very small area, most likely within the perimeter of the site, would have to be evacuated.

Radioactive material is also produced in a fusion power plant as result of the interaction of neutrons with the walls of the plasma vessel as well as with other structural materials. Preliminary calculations show that with an adequate choice of materials and with appropriate design provisions the amount and radiotoxicity of the waste can be strongly reduced. While the radiotoxicity of the waste in conventional fission power plants stays nearly constant even for a period of 500 years, the radiotoxicity of the fusion waste decreases by roughly four orders of magnitude on the same time scale. Recent studies demonstrate that a very large fraction of the fusion waste could be either suitably disposed of or recycled.

Another perspective to judge the environmental characteristics of fusion is to estimate the external costs of fusion. Using the ExternE methodology developed by the European Commission such studies indicate that the external costs of fusion are low and correspond roughly to those of photovoltaics or wind energy.

The economic competitiveness of fusion has been the subject of another investigation. Under the auspices of the Dutch energy research centre ECN a model for the future European energy market was developed. The costs of fusion were estimated following the results of system studies and industrial experience based on the construction of prototypes of the key components for ITER. The results indicate that fusion would fit well in an energy production mix with other renewable energy sources such wind and solar. While fusion could not compete cost-wise with current technologies such as coal-fired power plants or conventional fission reactors (under present conditions of implementation), the model shows that most renewable energy forms and fusion would penetrate the energy market when stricter environmental regulations are implemented to reduce the emission of greenhouse gases.

6. Concluding remarks

In the context of an energy mix in which the so-called renewable energies also play an important role fusion provides a potential solution to the global challenge of secure and

	sustainable energy supply in this century. Numerous evaluation boards, monitoring bodies and independent reviews on both the national and European levels have re-iterated the importance of fusion reseach and confirmed its high standard of excellence in Europe. Moreover, there is widespread agreement, both in the EU Commission and in the governments of member states that it is important to take the Next Step, namely, to realise ITER, as soon as possible. It is therefore incomprehensible that the discussions on the Sixth EU Framework Programme in 2001 have been overshadowed by politically inspired moves to cut drastically the funding in this key area of energy research.
9.	Which policies should permit the European Union to fulfil its obligations under the Kyoto Protocol? What measures could be taken in order to exploit fully potential energy savings which would help to reduce both our external dependence and CO2 emissions? Fusion has the potential in the long term to contribute massively to the reduction of CO2 emissions and to promote the security of energy supply.
10.	Can an ambitious programme to promote biofuels and other substitute fuels, including hydrogen, geared to 20% of total fuel consumption by 2020, continue to be implemented via national initiatives, or are co-ordinated decisions required on taxation, distribution and prospects for agricultural production ? This question might imply that hydrogen as a “substitute” fuel is a primary energy source. This is of course not the case. In fact, the production of hydrogen itself (e.g. by electrolysis of water) is a very costly process in terms of energy consumption.
11.	Should energy saving in buildings (40% of energy consumption), whether public or private, new or under renovation, be promoted through incentives such as tax breaks, or are regulatory measures required along the lines of those adopted for major industrial installations? Answer:
12.	Energy saving in the transport sector (32% of energy consumption) depends on redressing the growing imbalance between road and rail. Is this imbalance inevitable, or could corrective action be taken, however unpopular, notably to encourage lower use of cars in urban areas? How can the aims of opening up the sector to competition, investment in infrastructure to remove bottlenecks and intermodality be reconciled? Answer:
13.	How can we develop more collaborative visions and integrate the long-term dimension into deliberations and actions undertaken by public authorities and other involved parties in order to evolve a sustainable system of energy supply. How are we to prepare the energy options for the future? Before discussing future energy policies, a short review of the common practice in the past seems appropriate. The "Green Book" itself can serve as a starting point. It was

probably the drastic increase in the price of crude oil during 2000 which alarmed the political sphere and led to considerable activity in this area. This kind of reaction is not new: another example is provided by the German spending on energy research in the years 1970 - 1995, as shown in the Figure below. In fact, most OECD countries spent considerably more money on energy R&D in the aftermath of the oil crises of the 1970s than they do today. We must unfortunately conclude that energy policy has so far been largely dictated by the oil price rather than by a vision for the future!

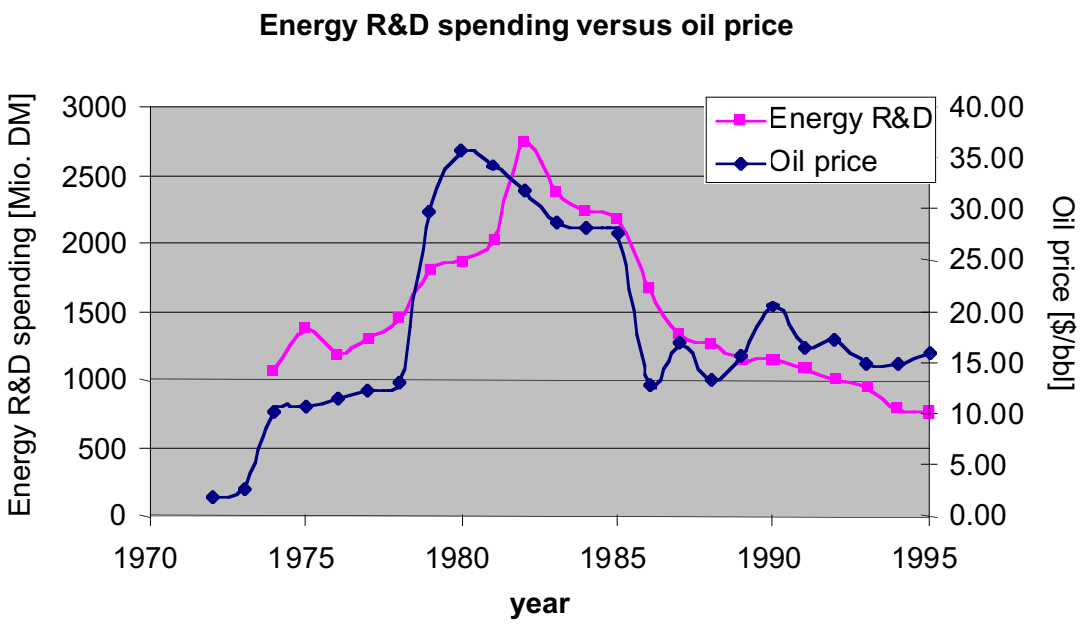

Figure: Energy R&D spending in Germany and the oil price 1970 to 1995.

Fortunately, there are some exceptions to this general trend, the most important being the "Kyoto protocol". Although the final outcome of Kyoto is not clear, the process itself and the committment of EU member countries to its main aims represents a success story which has important implications for the future. In particular, it means that factors other than short-term economic influences may help to guide future energy policy.

It is essential in the present situation to increase the money spent on energy R&D, even if this means increasing public spending: future societies will be able to cope more easily with debt than with a drastic shortfall in energy supply. A variety of well developed options is the best insurance to cope with the uncertainties of the future. Indeed, the recent past has shown that it is probably better for policy makers to take a more pessimistic view of the future.

Any other questions or proposals:

The "Green Paper" lacks a chapter discussing the European picture on a long-term (50-100 years) basis. Many of the problems of energy supply will have become acute even before the middle of this century. Moreover, the economic role of Europe is expected to

	be less significant in the 21st century, because the fraction of the world population living there is rapidly declining and the economic performance of other regions is expected soon to outweigh considerably that of Europe. In future, we must expect fierce competition on a global scale for the dwindling supplies of fossil fuel.