



EFDA

Socio-Economic Research on Fusion

Summary of EU Research 1997 – 2000

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Summary

In 1997 the European Community launched a program of Socio-Economic Research on Fusion (SERF), to answer to the questions:

What are the expected direct costs of electricity production by nuclear fusion?

What will be the environmental impact of fusion power production, and how do the associated “external” costs compare with those of other energy supply technologies?

Can fusion acquire a substantial share of the electricity market within the 21st century?

Will experimental fusion devices and series production power plants be socially acceptable?

The investigations were conducted using methodologies and mathematical models developed originally for non-fusion purposes, under the auspices of the European Union and the International Energy Agency. The conclusions of the first two stages of this effort - SERF1 (1997-98) and SERF2 (1999-2000) – are summarized in the present report. Additional contributions coming from the power plant availability study carried out under the EFDA Technology programme and from the underlying technology activities of the European Fusion Programme have also been incorporated.

Direct Costs of Fusion Power Production

The direct costs of fusion-generated electricity comprise the contributions from constructing, fuelling, operating, and disposing of, fusion power stations. An estimation of the capital costs was derived by a computer model, dividing the plant into about eighty systems that are individually costed. This costing model was benchmarked against the costs of the proposed large fusion experiment ITER, which are well established, as they have been derived in very detailed studies, mainly conducted by industry and in independent, parallel efforts by the ITER partners. The total capital cost, including interest rates during construction, was combined with estimated replacement costs, other operating costs, payments into a decommissioning fund and assumptions on availability, to obtain the cost of electricity. This was done in a standard manner, the “levelised cost” methodology, which is used for example in OECD and IAEA studies. Figure 1 shows the breakdown of the cost of electricity resulting from a typical set of assumptions.

The prediction of the absolute cost of fusion-generated electricity in more than 50 years from now requires in particular a realistic assessment of the uncertainties. A large number of calculations were therefore carried out, covering ranges of assumptions for the key physics and technology parameters affecting the economic performance of a power plant. The results indicate that the projected direct costs of fusion electricity are in the range 50-100 mECU(95)/kWh, with a most probable value of 70 mECU(95)/kWh. This may be compared to published projections of the direct costs of electricity from other possible future technologies in the second half of this century. The expected direct costs of fusion electricity are about fifty percent greater than those of coal (without emission abatement costs) or fission, but become competitive with “clean coal”, when emission abatement costs are included. Renewables vary greatly in their cost prospects, their range, and their capability to contribute to base-load power production. Fusion electricity is found to be competitive in production

costs with typical renewables, but can provide, in contrast to most of the latter, steady base-load power without additional energy storage costs.

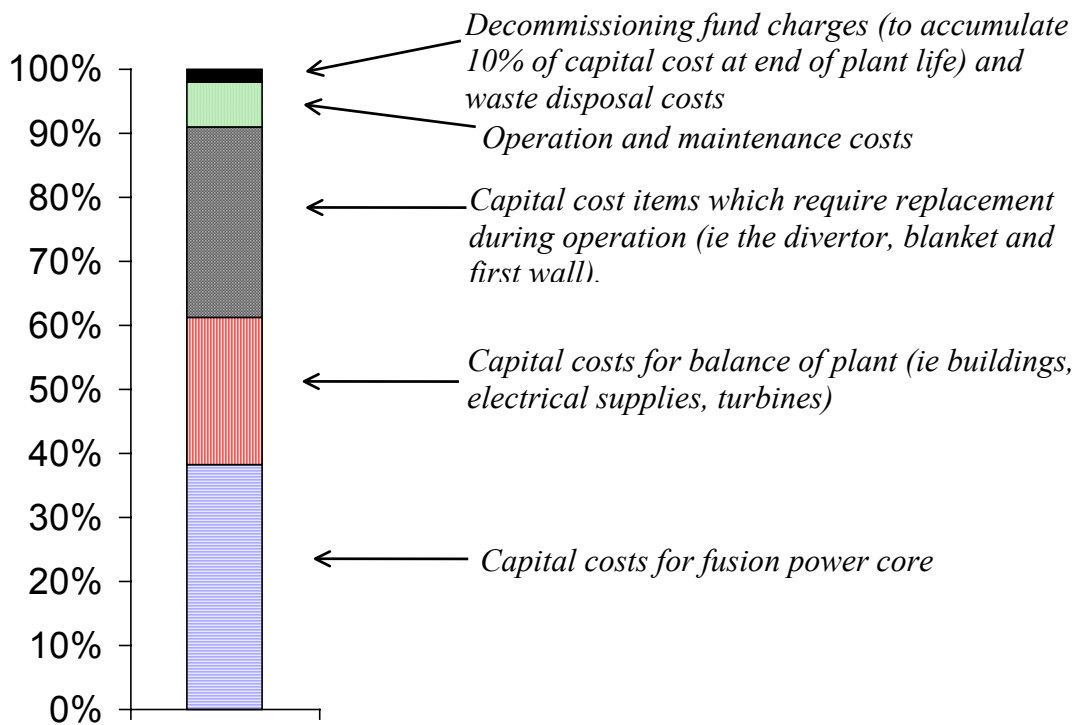


Figure 1. Composition of the cost of electricity from a fusion power station. Fuel costs, which are very small, are included under operation and maintenance.

External Costs of Fusion Power Production

The direct costs of electricity generation, calculated as described above, do not include costs such as those associated with environmental damage or adverse impacts upon health. A methodology for evaluating, in a standardised way, the external costs of electricity generation by different fuel cycles had been previously developed for the Commission of the European Union in the frame of the “ExternE” project, which involved more than 40 different European institutes from 9 countries. The ExternE methodology considers the effects of an additional fuel cycle located in a specific place. It assesses the entire life, fuel cycle and closure of a power station, including materials manufacturing, construction, and operation of the plant, dismantling, site restoration and disposal of waste. At each stage factors such as hazardous chemical or radioactive emissions, road accidents, occupational accidents, accidents at the plant exposing the public to risks and occupational exposure to hazards are considered

Under the Joule III programme of the European Union, the ExternE project had generated a large set of comparable and validated results, covering more than 60 individual power plant cases, for 15 countries and 12 different fuel cycles. A wide range of technologies had been analysed, including fossil fuels, fission power and renewables. Under the SERF1 and SERF2 programmes this methodology was extended to include fusion, evaluating the externalities for

a hypothetical power plant situated at Lauffen, a city in the vicinity of Stuttgart, Germany. It became apparent from these studies that fusion belongs to the class of low external cost power sources, with external costs amounting to only 1/40th of the direct ones. The major contribution to these external costs of fusion arises from the C14 produced in the cooling system, breeding blanket and structural components, which can be further reduced by a proper selection of the materials.

Major accidents do not make a measurable contribution to these externalities. This is true also for fission plants corresponding to the state-of-art in OECD-countries, due to the extremely low probability of major accidents. For fusion, in addition, even the consequences of an extremely improbable accident are low, leading to a negligible contribution to external costs.

Cost-effective European Energy Scenarios

The issue of whether, and under what conditions fusion could capture a share of the European energy market was examined by including fusion into the widely used MARKAL model, which simulates decisions to invest in and utilise energy technologies.

The MARKAL model designs scenarios minimising the cost of the entire energy system covering supply, distribution, and use of energy. It starts from input specifying, over the period covered, the level and pattern for the demand of energy, energy technologies, availability and prices of energy carriers, constraints or taxes on emissions (notably CO₂) from energy use, and discount rates. In the cost minimisation process it takes into account numerous constraints related to the load patterns of electricity demand, the intermittent character of some energy sources, growth constraints for technologies, etc. In the form used for the SERF studies the MARKAL model for Western Europe includes 350 end use technology applications (households, service, transport), 58 power generation technologies (including combined heat and power) and 120 other conversion technologies (including processes for biomass conversion, refinery processes, industrial processes).

The MARKAL studies showed that the market role of fusion in this century would strongly depend on the implementation of pollution reduction policies. In the unconstrained scenarios, fusion and renewables cannot compete effectively with coal. The energy system changes profoundly if CO₂ constraints are imposed. Introducing CO₂ – stabilisation targets into the calculations in the form of total emission budgets for the time period up to 2100, fusion starts entering the picture for target CO₂ concentrations below 650 - 550 ppm (pre-industrial level: 280 ppm; level in 1998: 360 ppm). For target concentrations between 550 – 450 ppm the installed fusion power reaches an imposed growth limit corresponding to 160 GW installed power in 2100. Renewables and fusion power grow approximately in parallel, with little direct competition between them due to their different role as intermittent and base-load power sources. These results are robust with respect to the broad range of variations in the assumptions made in the calculations.

Since each scenario is derived as an optimum, having the lowest discounted cost subject to the constraints, satisfying a given CO₂-target without fusion would be more expensive. The savings within this century associated with the inclusion of fusion in such scenarios depend strongly on the assumed economic development and the stringency of the CO₂ constraints, but can under realistic conditions also approach 1000 B€ for Europe alone.

Social Acceptability of Fusion

Sociological studies within SERF addressed two major topics:

- (1) Fusion as a large technical system, and
- (2) Fusion and public opinion.

Studies under the first heading addressed the organisation of fusion research as prime example of globalised research, and the interplay between public discourse and policy making (the issue of "governance"). One study analysed the characteristics of the European fusion associations and the attitude of researchers in the field, selecting the Swedish and German associations as differing representatives for more in-depth case studies. Two groups analysed, respectively, the history of the German "Energiekonsensdebatte" and the decision process leading to the abandonment of the Kalkar fast breeder project, as examples of previous political debates and decision processes concerning energy systems.

With large-scale commercial applications some 50 years in the future, fusion energy production and the associated benefits and risks are not yet a matter of public debate. Empirical sociological studies were therefore either restricted to groups with above-average prior knowledge of fusion (structured interviews with science journalists, environmental journalists, fusion and fission experts, members of environmental movements), or worked with focus groups, which received introductory briefings from both fusion advocates and critics. Both approaches showed differing expectations for the future energy mix (with everybody wishing for an increasing role for renewables), but also a rather broad agreement for a continuation of research into the fusion option.

The public interest and involvement in fusion affairs increases dramatically, when the more imminent issue of the placement of a major fusion research facility in the neighbourhood arises. This was the case for Porto Torres, which in 1997 was considered by the Italian government as a possible site for ITER. A study was conducted there based on the "European Awareness Scenario Workshop" procedure, previously developed under the auspices of the European Commission, to promote the citizen's participation in collective decisions concerning technology. It revolved around a structured discussion among 30 –50 people belonging to different social categories, and resulted in a strong involvement of the local participants and ultimately in an almost unanimously positive attitude towards the placement of ITER in their community.

Outlook

As - with the exception of the direct cost studies - the socio-economic investigations of SERF were the first efforts of their kind in fusion, their outcome highlighted in many areas the need for extensions and improvements. It has become apparent that SERF1 and SERF2 were only the start of a necessarily ongoing effort, which will need continuous updating not only to take into account the latest developments in fusion research, but also new information from other energy technologies. In some areas - notably in direct costs and externalities - these studies have also given important indications for the future direction of the European long-term technology programme.

Within the SERF3 programme, during 2001 - 2002, the socio-economic impact studies will be broadened to cover also other regions of the world. Long-term scenario studies with MARKAL programme have shown that, due to their different characteristics of intermittency, fusion and renewables can play a complementary role for the long-term energy supply. These aspects will be further explored by analysing the stability of such combined systems.

Crosschecks between US, Japanese and European costing models will be conducted to increase the confidence into the estimates of fusion power generation costs. A new conceptual power plant study has been initiated under EFDA, and will be conducted in close interaction with the safety and environmental impact assessments and the socio-economic studies.

The external costs are a valuable figure of merit for the environmental impacts. Their numerical value, however, cannot be simply compared with, or added to the direct costs. The external costs have so far been calculated on the basis of present-day prices and (in case of the non-fusion systems) based on present technology. It is to be expected that changes can be made to designs and operating practices for all energy technologies, which would reduce their external costs. Further ExternE studies will therefore include such possible technology advances also for non-fusion power plants.

Broad public involvement is now universally seen as a requirement for any decision process concerning major new technology developments. The Porto Torres project has shown that public acceptance studies assume a different quality, if conducted at a location actually considered as a site for a fusion installation. The major part of the sociological investigations in SERF3 will therefore concentrate on the Cadarache site proposal, to make a contribution to the public debate, but also to utilise the experience for field study projects.

1 Introduction

The future of nuclear fusion as an energy supply technology depends not only on the attainment of certain minimum physics and technology targets and the demonstration of major safety and environmental advantages, but also on socio-economic issues like competitive pricing, compatibility with the general energy supply structure and public acceptance. In 1997 the European Community therefore launched a program of Socio-Economic Research on Fusion, to respond to the questions:

- (1) What are the expected direct costs of electricity production by nuclear fusion?
- (2) What will be the environmental impact of fusion power production, and how do the associated “external” costs compare with those of other energy supply technologies?
- (3) Can fusion acquire a substantial share of the electricity market within the 21st century?
- (4) Will experimental fusion devices and series production power plants be socially acceptable?

The conclusions of these studies are summarized in this document. A detailed documentation of the methodology used and the assumptions made in these investigations is given in the referenced, publicly available reports. The emphasis given to the different topics here reflects primarily the relevance of the results as an input to the political decision process and for the further direction of the European fusion programme.

The work on direct costs required a deep understanding of fusion physics and technology, and was therefore performed by fusion experts. However, the economic methodology and calculations applied by them were standard, as recommended by several international agencies, and were verified by non-fusion experts.

The methodologies and mathematical models used for the work on external costs and energy scenarios were developed earlier, for non-fusion purposes, under the auspices of the European Union and the International Energy Agency. Non-fusion experts performed almost all of the work on external costs, energy scenarios and social acceptance issues.

These studies were conducted in two programme frames: SERF1 (1997-98) and SERF2 (1999-2000), with additional contributions made under the power plant availability study carried out in the EFDA Technology programme and the underlying technology activities of the European Fusion Programme.

The present report summarizes the outcome of the SERF studies conducted up to the end of 2000, integrating relevant contributions from other programme frames. The first three chapters build on each other, as the direct (chapter 2) and indirect (chapter 3) costs of fusion electricity production are key elements to determine its role in the long-term development of the European electricity market (chapter 4). The group conducting the direct cost estimates provided also the main interface to the reactor design, safety and environmental impact studies, which provided the input for the assessment of the external costs of fusion.

Public acceptance of fusion is a research object leading to contrasting conclusions, depending on the scale of the analysis. The public knowledge of fusion in general is scarce, and the general interest in details of a technology, which will experience large-scale deployment only in 50 years, is modest. It was recognized early on by the participants in this study that fusion

is not yet a matter of public debate, so that the opinion towards the *ongoing process of fusion R&D* or the opinion towards the *construction of the ITER experiment* should therefore form the primary object of sociological research. The temporary consideration of Porto Torres as a candidate site for ITER allowed conducting a realistic field test in the area of public attitude formation.

It has become apparent that SERF1 and SERF2 were only the start of a necessarily ongoing effort, which will need continuous updating not only to take into account the latest developments in fusion research, but also new information from other energy technologies. As - with the exception of the direct cost studies - the socio-economic investigations of SERF were the first efforts of their kind in fusion, their outcome highlighted in many areas the need for extensions and improvements. These items, which will be addressed in the upcoming continuation of SERF, are summarized in the final outlook chapter.

2 Direct Costs

The following authors and institutes/companies contributed to this study:

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2.1 Introduction

Although it is generally fusion's safety and environmental advantages, along with the large fuel resource, that motivates the development of fusion power, it is important that it also be economically viable. One aspect of the economics is determining the probable direct costs of fusion. The term "direct costs" refers to the contributions to the cost of electricity from constructing, fuelling, operating, and disposing of, power stations. These are the subject of this section and should be considered along with the external costs, which are discussed separately. The other important issue for economic viability is the future energy market in which fusion should compete; this is discussed briefly here but in more detail in the section on long-term scenarios and the role of fusion power.

There have been several studies, independently in Europe, USA and Japan, of the direct costs of electricity generation by fusion power stations, and the sensitivity of those costs to the performance of materials and to plasma conditions. In this report, the European work is summarised, with brief reference to work elsewhere.

As an introductory point, it is interesting to consider the reliability of determining the likely costs of electricity using a technology that is not yet fully developed. We will see later the breakdown of expected costs but, broadly speaking, the fusion-specific items (reactor core, tritium plant...) make up around half of the capital cost of the power plant, the remainder being conventional items such as buildings and turbines. In the fusion core, the largest cost item is the magnets: superconducting magnets presently designed using conventional technology assumptions. All other items foreseen for a fusion power plant are included and costed, but given that each item makes only a relatively small contribution to the overall power station cost, errors in costings do not introduce substantial errors in the final cost of the power plant. The main exception to this insensitivity is the magnet technology, where expected developments in superconducting technology will naturally be to the advantage of fusion.

In addition to the cost of the power plant, there are three other important issues which determine the cost of electricity: the net electricity production, determined primarily by physics performance and thermodynamic efficiency; the amount of time that the power plant is available for power production, determined primarily by the frequency of replacement of in-vessel components, and the cost of replacing those in-vessel components. In the following discussion, each of these items and their interaction is described.

2.2 Determining the Costs

In the SERF programme there have been several approaches to determining the direct costs of fusion power. The majority of the work has been carried out using a mathematical model

(PROCESS) of the engineering, physics and costings of a commercial fusion power station [1,2,3,4]. The capital costs are derived, by dividing the plant into about eighty systems that are individually costed. The total capital cost, including interest during construction, is combined with estimated replacement costs, other operating costs, payments into a decommissioning fund and availability, to obtain the cost of electricity. This is done in a standard manner, the “levelised cost” methodology, which is used for example in OECD and IAEA studies. Details can be found in reference 1.

The models used in the PROCESS code are continuously updated in line with developments in fusion research, particularly driven by results from the international effort to design an experimental reactor: ITER. In addition, the calculations are compared with results from other studies, for instance from the US ARIES team [5], as well as other European studies [6,7].

The costs were benchmarked against the costs of the proposed large fusion experiment ITER, which have been highly validated in detail by international teams of engineering consultants, and by comparisons with other published estimations of power station costs. ITER is not an electricity-generating device, so a complete comparison could not be made. For the many cases where a comparison could be made, the agreement, as shown in figure 1, was very good, typically within ten percent [1,2]. The only exceptions to this are the items, which are genuinely more complex in a power plant than in ITER, particularly the blanket and shield structures and the first wall. The costs of these items are expected to be higher from PROCESS because they represent a full power plant, with more stringent requirements than ITER.

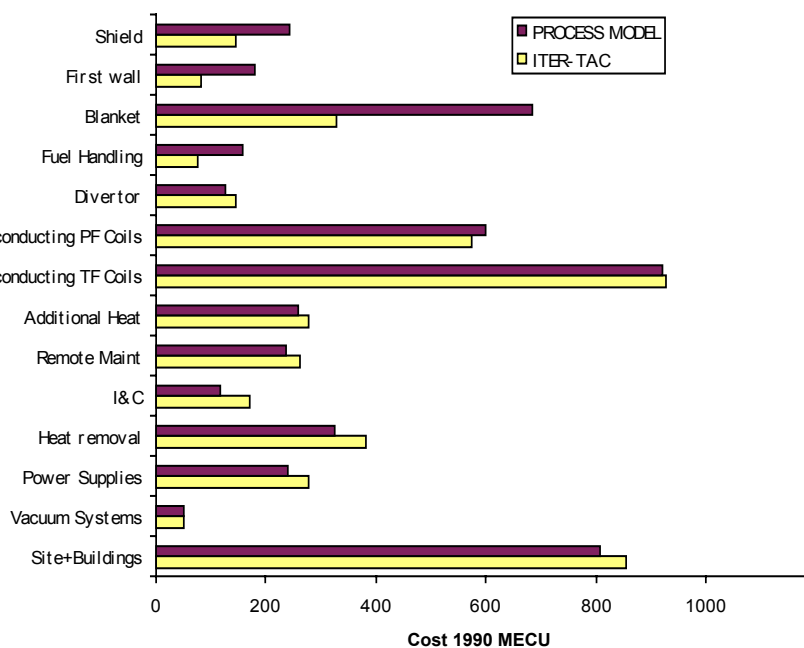


Figure 1: Comparison of costs derived for ITER using PROCESS, compared to the actual ITER cost estimates. (I&C refers to instrumentation and control).

The model was then used to infer the costs associated with a future commercial fusion power station. Figure 2 shows the composition of the cost of electricity in a typical calculation [1]. All other cases are similar.

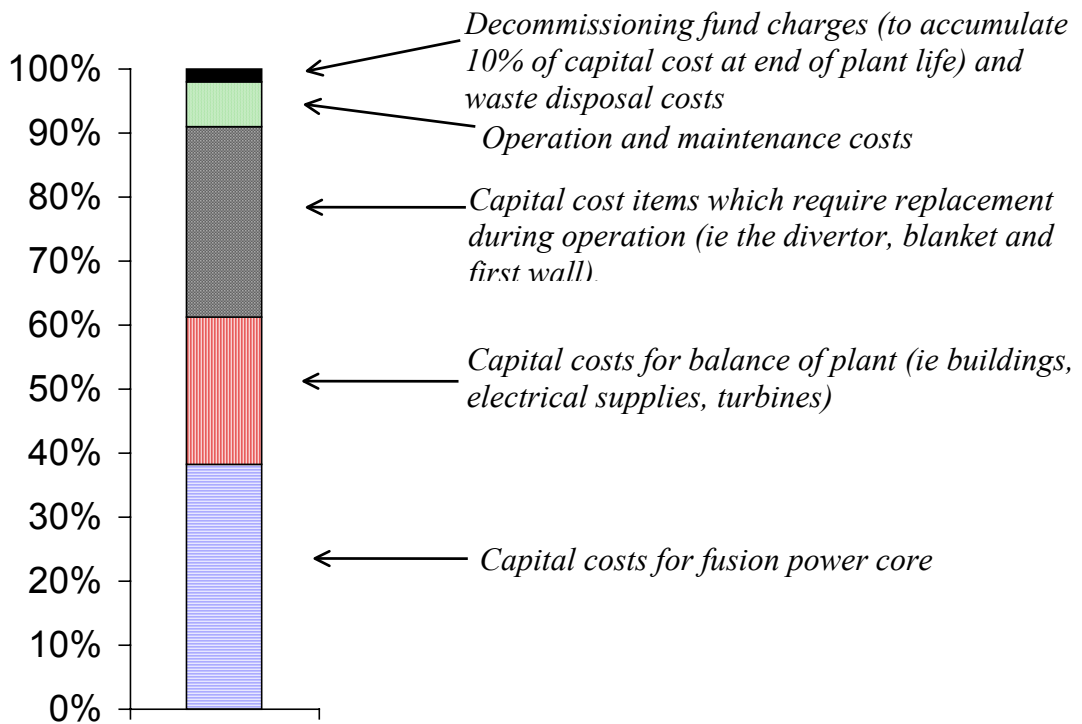


Figure 2. Composition of the cost of electricity from a fusion power station. Fuel costs, which are very small (of the order of 0.5%), are included under operation and maintenance.

Additional work on fusion's direct costs has been carried out, in part independently of the fusion programme, for instance benchmarking extrapolations of power plant costs and examining the impact on costs of progress in 1. fusion development and in 2. commercialisation [8,9].

As an example of this work, reference [9] also looked at the potential for cost savings, which accrue from siting two fusion power plants on the same site. Considerable cost benefits were identified.

Although the ITER costs discussed above are for a first-of-a-kind device, the fusion power plant costings given later are assumed to be for a 10th-of-a-kind device. Clearly significant cost savings can be expected after constructing 10 fusion power plants. Such cost savings are assumed to apply only to the fusion specific equipment and published values vary from a conservative 20% to a more ambitious 50% cost reduction. A 50% reduction for a 10th-of-a-kind corresponds to a 20% cost reduction for each doubling of production and this is actually the median value observed over a wide range of industries [10]. A further useful point of reference is that fission (PWR) experience shows a typical *overall* cost saving of about 30% when a twin of an existing plant is constructed. To reflect uncertainty over the appropriate cost reductions to apply for a 10th-of-a-kind device, a range of values will be considered here.

Varying physics, technology and economic assumptions impact on the cost of fusion electricity. As an introduction to this, the impact of varying two of the most important parameters are shown here, figure 3. These are the unit size of the power plant – its net electrical output – and the main physics parameter, the plasma pressure normalised to the energy density of the magnetic field, which measures the amount of plasma energy that can be

contained in a given device. The unit size is important because of important savings of scale in a fusion power plant, both because the fusion power increases more quickly than the costs and the re-circulating power needed falls as a fraction of the total power. The normalised pressure, β_N , is important because it determines how much fusion power can be produced in a given sized device with a given magnetic field strength. Both of these factors have similar beneficial impacts on the calculated cost of electricity.

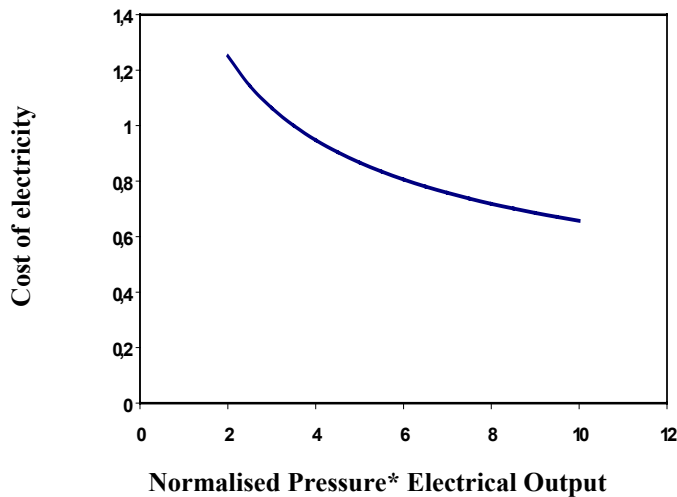


Figure 3: The economics of fusion are improved substantially by increasing the electrical output of the power plant, or the normalised pressure, an important measure of the physics performance. (Cost of electricity in relative units, Electrical power in GW).

2.3 Range of Cost of Electricity

During the period 1997-2000, many improvements were made to the modelling of the fusion power plant, and an improved understanding was gained of the role of the key physics and technology issues in reducing costs. Then the model was used to predict the direct cost of fusion electricity on varying assumptions about physics and technology performance. Comparisons were made with the published direct costs of electricity from other technologies.

A large number of calculations of the cost of electricity from fusion power stations were made with the model, covering ranges of values over which the key physics and technology parameters may vary [4]. These ranges were centred on best estimates, with a spread of more pessimistic or optimistic values. For the plasma physics assumptions, the best estimates corresponded broadly to performances about thirty percent better than the conservative design basis for ITER, which assumes some progress in the course of ITER experimentation and in parallel work. For the uncertainties relating to materials and components, the best estimates corresponded to the expected performance, in fusion power station conditions, of near-term materials. This assumes that materials, such as those that have performed well in present-day tests of high heat-flux components and blankets, will perform according to our understanding in fusion power station conditions.

Table 1 shows a range of assumptions for some of the key physics and technology variables. These are broadly designed to cover the range of other studies that have been carried out, and vary from values that are likely to be readily achievable to values that are an optimistic

extrapolation from the present position. Using this range of assumptions, a range of power plant designs were used to determine the likely cost of fusion electricity, although it is important here that it has been considered improbable that either all the pessimistic assumptions or all the optimistic assumptions will be simultaneously combined in one power plant.

Variable	Minimum	Mean	Maximum
Discount Rate (%)	5	7.5	10
10 th of a kind factor	.5	.6	.7
Unit Size (GW)	1	1.7	2.5
Normalised pressure	2.5	4	5.5
Limiting density	0.7	1	1.4
Thermodynamic efficiency	0.35	0.48	0.6
Availability	0.6	0.7	0.8

Table 1: Ranges of assumptions about key inputs for determining the probable range of cost of electricity.

Figure 4 shows the calculated relative likelihood of the cost of fusion electricity. This is the number of calculated outcomes that fall into the cost bands shown.

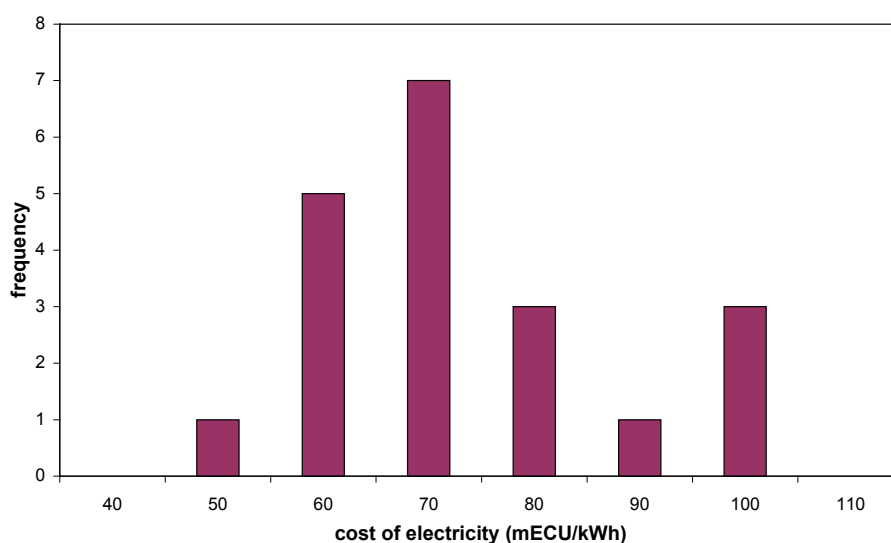


Figure 4: Relative likelihood of the direct cost of electricity from fusion power stations.

It is apparent from figure 4 that the projected direct cost of fusion electricity are in the range 50-100 mECU(95)/kWh. It is important to note that the assumptions made to obtain this result specifically excluded the possibility that substantial progress in all areas may be achieved, but rather attempted to balance progress in some areas with lack of progress in other areas. If the most optimistic assumptions were instead all combined, the cost of electricity would be approximately half of the lowest end of the range shown in figure 4. Although this is not likely to be necessary for fusion to play a role in a future energy market, it is clearly a rewarding target for continuing fusion research and development.

2.4 Important Variables

Having studied a range of possibilities for a fusion power plant, it is possible to determine the way that the cost of electricity varies with each variable and so to determine the most important factors in improving the economics of fusion. As has already been noted, improvements in superconducting technology will be beneficial for fusion. However, in this study, the superconducting properties are held constant and only those parameters that are likely to be improved within the fusion programme are considered. It is found that, apart from the obvious importance of economic assumptions – the discount rate and the cost reduction due to series production – the order of merit for improving economics is:

- availability – the fraction of the time the power plant is available to produce electricity;
- high thermodynamic efficiency – the ratio of electrical to thermal power, improved by more advanced, higher temperature blankets and divertors;
- normalised pressure – the measure controlling how much fusion power can be produced in a given device;
- unit size – the net electrical output power, and
- limiting plasma density – the highest particle density that physics constraints will allow.

Although this represents the order of merit for improving fusion economics, in fact the relative importance of at least the first four items is not very different. It would be beneficial to improve performance in each of these areas. Work on the direct costs of fusion generally concentrates on the impact of physics and technology developments on power plant design and economics, without self-consistently including the implications of availability. To address this deficiency, a specific study has been carried out, including in the conceptual power plant designs a self-consistent calculation of the availability, based on parameterisation of the lifetime of components.

The PROCESS code has been modified to model the availability of a fusion power plant, for instance by determining the lifetime of the blanket that surrounds the plasma in terms of the number of full power years of operation. It is assumed that the blanket life is limited by the amount of energy that each square metre can absorb, that is the power density multiplied by time. By making assumptions about the time required to replace the blanket, the unavailability due to blanket replacements is determined [3,11,12]. An example of a result from this modelling is shown in figure 5, which shows the way that availability increases as the tolerable blanket fluence (the number of years multiplied by the power density crossing the first wall) is varied.

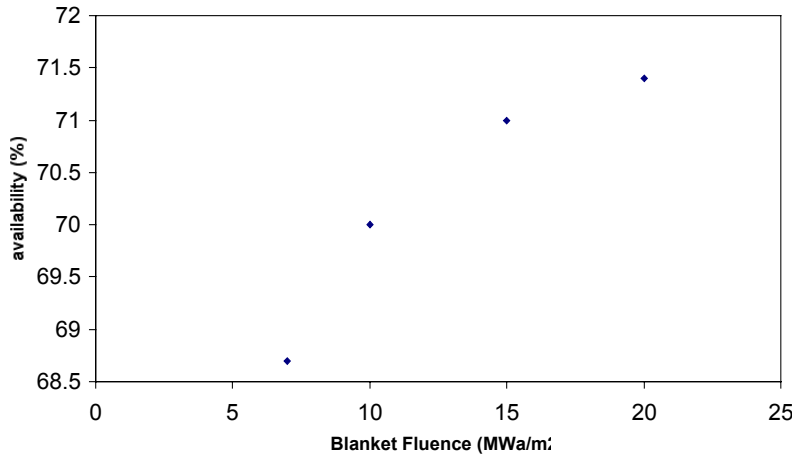


Figure 5: Improvement in power plant availability as the tolerable blanket fluence is increased. There is little gain in increasing beyond 20 MW·years/m².

An important aspect of the availability modelling is that it tends to increase the optimum power plant size compared to models, which do not self-consistently model the availability. Although the results are not yet firm because of the uncertainties in lifetimes and replacement times, the inclusion of such modelling has already shown important trends and directions for further investigation. An illustrative calculation is shown in Figure 6 where the variation in the optimum size of power plant is shown as the time required to exchange the internal components is varied. The design moves to larger major radius to reduce the power density, increasing the lifetime of components and preventing the availability falling too low. In this example the time between replacements doubles with the increased shutdown time, keeping the availability above 70%.

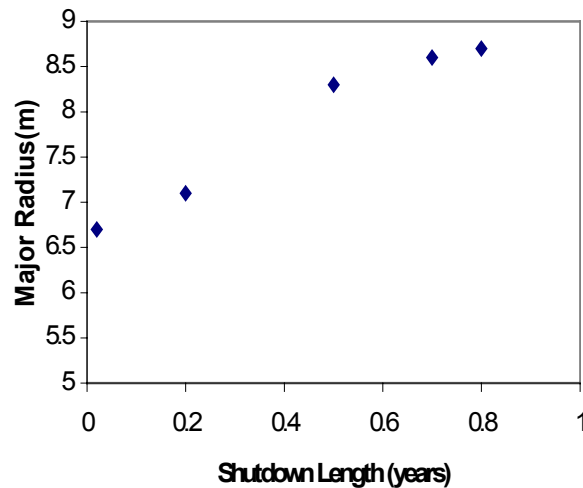


Figure 6: Illustrative calculation of the variation of optimum major radius as the length of shutdowns increases. To maintain high availability, the machine size increases, reducing the power density and increasing the lifetime of components.

2.5 Comparison with Other Electricity Sources

Having derived a range of costs for fusion electricity, it is interesting to look at how this compares with other sources, when the costs are derived on the same basis. Although such comparisons are best made in the context of scenario models of the future energy demands and constraints, it is possible to make a simple comparison of costs here.

In order to make comparisons with other energy sources likely to be contributing to the future energy market, it is necessary to look at independent predictions for such sources [13,14,15,16]. An important aspect of this comparison is that it should be for base-load, or firm, power production, requiring intermittent sources to be buffered by energy storage systems in order to match supply to demand. In addition, the increasing pressure to reduce pollution impacts, including greenhouse gas emission is incorporated, again using independent assessments of carbon sequestration costs. These technologies, for energy storage and carbon sequestration are relatively uncertain or, more precisely, are expensive as presently foreseen, however future developments are likely to reduce costs. As in the case of fusion, the range of possible future costs is quite large. This is not surprising given the wide range of generation costs even for present or near term technologies [13]. This is consistent with a wide variation in electricity costs around the world [17] and also variation with time, and highlights the expectation that different countries will take different views of a new energy technology, depending on their own, current position.

Broadly, the outcome of these studies is that the expected direct costs of fusion electricity are competitive with typical renewables (without storage costs), and significantly higher than coal (without emission abatement costs) or fission. With the inclusion of emission abatement costs, fusion direct costs are competitive with those of clean coal. The costs of electricity storage, which would be needed if many renewables were required to provide firm power (if other technologies were suppressed), mean that fusion will be competitive with the best of renewable technologies, in direct cost terms. The implications are that without pollution controls, coal would be favoured, or, without constraints on fission, fission would be introduced widely. However, the present trends towards low emissions, low external cost systems suggest that fusion, along with renewables, can have a role to play in the future energy market. Further considerations of the future energy market rely on the use of scenarios models to explore possible outcomes, and this is discussed separately.

2.6 Outlook

In summary, there is a significant amount of work worldwide, looking at the conceptual design of fusion power plants and the consequences for economics as well as safety and environmental attractiveness. Different studies give emphasis to different areas but inter-comparisons show that using the same assumptions, the same results are achieved.

The direct costs show that a reasonable extrapolation of the present status of fusion research is expected to allow a future power producing plant with economic performance comparable to projections for other sources, such as clean coal and renewables. With the expected advances in physics and technology, it is probable that the costs will fall further. The role of fusion in a future energy market is a more complicated issue than implied by simply comparing the ranges of projections of cost of electricity: much more can be learned by using scenario modelling to investigate the role of fusion in plausible models of energy markets. This is discussed later in the report.

Apart from physics issues of how much power can be obtained from a given sized power plant, there are important aspects of power plant conceptual studies, particularly availability, which should be included in the analysis, as accurately as possible. Self-consistent availability modelling impacts on the design and economics of conceptual power plants and has therefore an important role to play in the studies.

The main prospects for improved economics lie in improving the normalised pressure, and in technology developments to improve efficiency and availability. The prospects for significant improvements in superconducting materials also look good and this will be of considerable benefit to fusion.

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3 External Costs of Fusion Power

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3.1 Introduction

CO₂-emissions, sulphur emissions, emission of radioactive materials, traffic accidents and the destruction of a beautiful landscape by overland transmission lines are all consequences of the world energy system. Energy is one of the most important production factors for a modern economy but energy production has a big impact on the environment and human health.

While the economic activities are ruled only by the cost and prices expressed in money values, the impacts on environment and human health are of very different nature starting in the extreme with the loss of a human life and ending with the destruction of a beautiful landscape. To compare these different aspects seems to be a comparison between pears and apples. But practical life does of course demand a comparison of these different aspects, when for example a decision on a new power plant is made.

The methodology of external costs - as presented below - is an attempt to rationalise the process of comparison by boiling down all the different aspects to one number: the external costs. Evaluation of external costs is less a classical appraisal of the effects of a technology on human health and environment, it is more an interpretation of these results.

Within the European Commission R&D Programme Joule II, the ExternE Project developed and demonstrated a unified methodology for the quantification of the externalities of different power generation technologies [1,2]. Launched in 1991 as a collaborative project with the US-DOE, and continued afterwards by the EC as the ExternE project, it has involved more than 40 different European institutes from 9 countries, as well as scientists from the US. This resulted in the first comprehensive attempt to use a consistent 'bottom-up' methodology to evaluate the external costs associated with a wide range of different fuel cycles. The result was identified by both the European and American experts in this field as currently the most advanced project worldwide for the evaluation of external costs of power generation.

Under Joule III, this project has been continued with three distinct tasks. The Core programme was oriented toward refinement of the methodology and to apply the methodology to parts of the energy sector not explored previously [3,4]. The ExternE Transport programme adapted the methodology for the characterisation of the impacts and damages of the transport sector [4]. And the third one, ExternE National Implementation programme [5], whose objective was to establish a comprehensive and comparable set of data on externalities of power generation for all EU member states and Norway. The National Implementation project has generated a large set of comparable and validated results, covering more than 60 cases, for 15 countries and 12 fuel cycles. A wide range of technologies has been analysed, including fossil fuels, nuclear and renewables. Fuel cycle analyses have been carried out, determining the environmental burdens and impacts of all stages. Therefore, besides from the externalities estimated, the project offers a large database of environmental aspects of the fuel cycles studied. The methodology for assessment of the externalities of transport has been recently updated within the project and also some improvements have been incorporated to the general ExternE methodology within the project “External costs of energy conversion – Improvement of the ExternE methodology and assessment of energy related transport externalities”[6].

Results from the ExternE have been recently cited in several EU documents regulating subsidies for renewable energies [7].

Under the SERF programme the ExternE methodology was extended to include fusion, evaluating the externalities for a hypothetical power plant located in Lauffen, a city in the vicinity of Stuttgart, Germany. The fusion-specific data were initially taken in the SERF1 studies from the results of the European Safety and Environmental Assessment of Fusion Power (SEAFP), for the two power station concepts studied in SEAFP [8]. The externalities work was later updated in the SERF2 studies to include a further power plant model, developed and analysed in a follow up study of SEAFP.

Several research institutions from different European countries have participated in the externalities work under SERF1 and 2 studies. The overall work has been co-ordinated by Euratom/CIEMAT Fusion Association (Spain), which also was in charge of the estimation of the externalities in the operational and upstream phases of the fuel cycle. Other institutions participating in the projects were:

- Euratom/IPP Fusion association (Germany) contributing to technical aspects in SERF and in charge of the analysis of the consequences of a large fusion economy in SERF2.
- Studsvik Eco & Safety AB, Association Euratom-NFR (Sweden), in charge of the estimation of externalities of decommissioning of the fusion plant and site restoration, and the sensitivity analysis.
- VTT, Association Euratom-Tekes (Finland), in charge of the aspects related to waste disposal and global effects of a fusion economy on CO₂ avoidance and C-14 radiation.
- Euratom/UKAEA Fusion Association (United Kingdom), in charge of technical aspects in SERF2.
- CEPN, Association Euratom-CEA (France), contributing with the analysis of radiological accidents and sensitivity analysis of plant location.

- RISØ National Laboratory (Denmark), contributing to the analysis of the materials manufacturing stage and in charge of the comparison of renewable energies and fusion externalities.
- ENEA (Italy), contributing with an analysis of the economic impacts of a large fusion facility in Porto Torres.

3.2 ExternE Methodology

The methodology used for the assessment of the external impacts of the fusion fuel cycle is the one developed within the ExternE project. It is a bottom-up methodology, with a site-specific approach, that is, it considers the effects of an additional fuel cycle located in a specific place.

Quantification of impacts is achieved through the damage function, or impact pathway approach. Emissions and releases are traced from the source over various steps to the impact. An example is the release of a radioactive isotope from the stack to the air, the distribution in the air, the transport from the air to some soil and then into some food, which is later ingested by a human and might cause cancer. This allows for a marginal, site-specific assessment, and using the same methodology for all fuel cycles allows for a consistent comparison among them.

The stages in which the methodology proceeds are the following:

- ***Site and technology characterisation***

One of the distinguishing features of the ExternE methodology is the inclusion of site and technology specificity. The fuel cycle stages will have to be fully characterised, taken into consideration the activities over the lifetime of the plant, from the extraction of the materials needed to construct and operate the plant to the final decommissioning of the plant and disposal of the waste. By-products have to be taken into account up to the point when they are ready to be used elsewhere.

The use of the impact pathway approach requires also a detailed definition of the scenario under analysis in physical terms and the spatial limits of the analysis should be designed to capture impacts as fully as possible. The same applies to the temporal limits. In principle, each impact should be traced for as long as it is considered to be relevant.

- ***Identification of fuel chain burdens and impacts***

The term 'burden' relates to anything that is, or could be, capable of causing an impact of whatever type and the potential impacts of these burdens.

- ***Prioritisation and quantification of impacts***

Once we have selected the impacts to be analysed, those producing the highest externality according to previous knowledge or expert judge, the impact pathway for each case has to be defined, so that impacts can be quantified. In some cases these pathways are very simple, while in others the description of these linkages is far more complex.

The first stage of the impact pathway is to determine the consequences or burdens derived from the selected site and technology option. Besides from quantifying them, these consequences have to be distributed along time and space, taking into account the system boundaries that have been previously defined. The *stock at risk* has to be determined. This is the number of receptors, be it human population, ecosystems, or other, which are likely to be

affected by the consequences of the cycle. Then, the impacts are quantified linking this stock at risk with the impact functions. Impact functions can be rather straightforward, in some cases. However, other impacts require the use of more complex dose-response functions. Health impacts over the general public are a priority impact in all the fuel cycles analysed. These effects can be produced by conventional pollutants namely particulate matter, SO₂, NO_x, O₃, CO, heavy metals, dioxins, and other, or radiological emissions. The effect of these radiological emissions in different stages of the life cycle of the fusion power plant is the focus of the assessment of the fusion fuel cycle. The construction, operation, and dismantling of a fusion facility can lead to an increased exposure to ionising radiation for both the workers and the general public, which in turn can lead to both deterministic and stochastic effects in humans. Since during normal operation all individual exposures will be below threshold values for deterministic effects, these effects are not considered in the normal operation analysis. For stochastic effects, it is assumed that there is no threshold level and that the dose-response functions are linear with no offset. With these assumptions, the collective dose to the population can be used to calculate the total number of expected health effects. Assessment of stochastic health effects has been made using the risk factors recommended by the ICRP [9] for the occurrence of fatal and non-fatal cancers and severe hereditary effects.

- ***Economic valuation***

The approach followed for economic valuation of impacts is based on the quantification of individual 'willingness to pay' (WTP) for environmental benefit. A limited number of goods - crops, timber, building materials, etc. - are directly marketed, and for these valuation data are easy to obtain. However, many of the more important goods of concern are not directly marketed, including human health, ecological systems and non-timber benefits of forests. Alternative techniques have been developed for valuation of such goods, the main ones being hedonic pricing, travel cost methods and contingent valuation.

Valuation of human health effects and specially mortality effects is a very controversial matter. Valuation of mortality impacts was performed in the 1995 ExternE methodology using the concept of Value of statistical life (VSL). This is based in the estimation of the willingness to pay (WTP) for a change in the risk of death. However, a number of questions were raised regarding the use of the VSL for every case of mortality considered. These questions related to the fact that many people whose deaths were linked to air pollution were suspected to having only a short life expectancy. In view of this, the ExternE methodology explored valuation on the basis of life years lost. For quantification of the value of a life year (VOLY) it was necessary to adapt the estimate of the VSL. Within the ExternE methodology it was concluded that VSL estimates should be restricted to valuing fatal accidents, mortality impacts in climate change and similar cases where the impact is sudden. The VSL should not be used in cases where the hazard has a significant latency period before the impact, or where the probability of survival after impact is altered over a prolonged period. In this cases the value of life years lost approach is recommended.

As costs and benefits are distributed along wide time periods, they have to be brought to the present time in order to be compared on the same basis. This is done by discounting. The higher the discount rate, the lower the value attached to future damages or benefits. Two central discount rates are used in the ExternE methodology: 0% and 3%, with an intermediate value of 1%. Selection of the discount rate to be applied here is an important issue because many of the damages of the fission and fusion fuel cycles will occur many years after the action that causes the damage actually takes place. The application of any discount rate above zero can reduce the cost of major events in the distant future to a negligible figure and may shift the cost burden to future generations. The approach followed in the ExternE estimations of fission fuel cycles externalities and also the approach used here is the consideration of a 0% discount rate following a sustainability criterion [3].

- ***Assessment of uncertainty***

Uncertainty arises in each stage of the assessment. When identifying the consequences of each activity, there may be errors in the estimation, due to the variability of data, or the need to extrapolate them. In the case of fusion technology this source of uncertainty becomes especially important. The quantification of the impacts is also uncertain, mostly due to the complexity of the phenomena involved. There is a lack of detailed information on human and ecosystem responses to pollution or other impacts, and so several assumptions, which may prove unfounded, have to be made.

Economic valuation also presents many caveats. It involves modelling the behaviour of consumers and producers, and projecting future scenarios, as well as making political and ethical decisions, such as the choice of the discount rate.

Uncertainty should be treated using traditional statistical techniques. Unfortunately, in most cases the shape of the probability distribution is unknown, so this is not possible. Instead, other methods are required, such as sensitivity analysis and expert judgement. The uncertainties of each stage of an impact pathway need to be assessed and associated errors quantified. The individual deviations for each stage are then combined to give an overall indication of confidence limits for the impact under investigation.

The ExternE updated methodology [3] recommended the use of uncertainty labels for each impact with a more or less quantitative definition based on geometric standard deviations σ_G and confidence intervals of the lognormal distribution.

3.3 Prior applications of ExternE to other power production systems

Under the ExternE National Implementation project [4], the ExternE methodology was applied to more than 60 cases covering 12 different fuel cycles in 15 different countries.

Main results from the project are shown in figure 3 in the results section. This project has considered a very broad range of technologies, fuel and pollution abatement options. Therefore, due to the site and technology specificity of the methodology, the results may be quite different and it is reflected in sometimes large error bars.

In general terms, fossil fuels, specially coal and lignites, present the largest external costs. Renewable energy sources show the lowest externalities, mainly due to their CO₂-free character and to the low related pollutant emissions, with the only exception of biomass cycles since TSP (Total Suspended Particles), and NO_xs emissions produce rather high damages. Nuclear fuel cycle has low external costs compared to other technologies. The reason for this can be found in the nature of the methodology used for estimating the external costs. The most important public concerns for this fuel cycle, radiological accidents and waste disposal, are difficult to evaluate in terms of external costs. In the case of severe accidents, the methodology used here is based in the expected value approach, which neglects consideration of risk aversion attitudes in the general public and fails to capture the lack of social acceptability of fission power. In the case of waste disposal, the effects of possible exposures to radioactivity released from the repositories are delayed to very far points into the future and their magnitudes become, even without discounting, very reduced.

3.4 Limits of present analysis

Under SERF 1 and 2, the ExternE methodology has been applied to fusion as a power source. This is a new application of the methodology insofar as fusion is not a mature applied technology but still an object of R&D and it will take several decades before fusion might become an economic reality. Still for reason of convenience it was done as if fusion would be

applied today. The comparison of a technology available not before 2050 and current technologies is of course strongly biased. Progress in various competing technologies like coal and fission power plants can be envisioned that might reduce their external costs considerably. Future work is needed to bring this comparison to a more equal basis.

This future work needs to consider both changes in the technologies and the underlying source terms and in the affected environment - like new forms of agriculture - and changes in human behaviour - like new ways of nutrition. The possibility to infer all these changes is of course strongly limited.

3.5 Results

3.5.1 Technology aspects

The site selected for the implementation of the fusion power plant has been Lauffen (Germany). The reference technology is a hypothetical fusion power plant of 1000 MW that would be installed around 2050. For the reactor core three different models have been considered, differing in the used cooling medium and blanket concept [10]. The basic plant models are shown in table 1.

Table 1. Plant models characteristics

Plant Model	FW/blanket structure	Tritium-generating material		Neutron multiplier	FW/blanket coolant	Fusion power	Electrical power
1	Vanadium alloy	Li ₂ O ceramic pebble bed		None	Helium	3000	1000
2	Low activation martensitic steel	Liquid Li ₁₇ Pb ₈₃		Li ₁₇ Pb ₈₃	Water	3000	1000
3	Low activation martensitic steel	Li ₄ SiO ₄ ceramic pebble bed		Beryllium	Helium	3000	1300

The changes to the plant concepts, the more realistic materials and the switch to a stainless steel shield (which has the effect of reducing the C-14 generation but increasing other nuclides, such as Nb-94) are the main changes introduced in SERF2 over the assumptions underlying earlier SERF1 work.

One of the key aspects of the environmental and safety properties of fusion is the activation of the materials exposed to neutrons. The development of low activation materials is addressing this issue, but the choice between different materials has still to be made. There are developments in recycling opportunities that can considerably reduce waste volumes and vary with materials. The most important external cost identified in the earlier SERF-1 study was the C-14 generated during the power plant operation. The main source of C-14 is the nitrogen in steels and the oxygen content particularly of the water coolant in plant model 2 and the breeder materials in plant models 1 and 3. The nitrogen content of steels could be dramatically reduced, indeed SS-316 (stainless steel) contains a factor of 5 less nitrogen than OPSTAB (low activation alternative), both materials that were considered for shield materials in the recent SEAFP-2 study. There is still potential for further reduction so that the shield contribution becomes relatively unimportant leaving the coolant and breeder materials as the

dominant sources. In this case there would be an overall reduction in C-14 by a factor of 5 to 10.

Another area of development over recent years has been the consideration of recycling possibilities for materials at the end of the power plant life. In SEAFP-2 it was considered that almost all materials could either be cleared as non-active materials or recycled for use, for instance, in another fusion plant.

One additional outcome of the more recent studies is the reduced level of occupational exposure envisaged in a future fusion power plant. This was of concern in SEAFP but attempts to optimise water chemistry (for plant model 2) indicate that the collective occupational radiation exposure could be reduced to levels below 1man-Sv per year for all models.

Finally, in the area of routine releases from the power plant, there has been little new work and the results available previously are still relevant.

3.5.2 *Assessment of externalities*

The whole fuel cycle was analysed from the extraction of materials to the disposal or recycling of fusion waste.

- ***Upstream and power generation stages***

Upstream stages of the fusion fuel cycle analysed in this study are the manufacturing of materials and the construction of the power plant. Impacts from fuel supply and fuel transport stages have been considered negligible due to the reduced amount of fuel required for the operation of the fusion power plant.

The assessment of impacts is primarily focused on radiological impacts on both workers and the general public, including fatal and non-fatal cancers and hereditary effects. In addition occupational and traffic accidents leading to deaths and injuries are analysed. For the non-radioactive pollutants emitted from the fusion cycle, mainly in transport activities and manufacturing of construction materials, the set of impacts assessed for fossil fuel cycles and transport in the ExternE methodology are considered based on previous work performed on these cycles [3,4]. These impacts include effects on public health, crops, materials, ecosystems and global warming.

Results obtained revealed that for plant model 2, the prevalent cause of external costs were the collective doses produced by the global dispersion of C-14 emissions as they enter in the global carbon cycle and become widely dispersed throughout the world. The impacts produced by global dispersion of C-14 have been integrated over a period of 100000 years. Occupational impacts of the plant, and the impacts indirectly caused by the energy use on the manufacturing of materials were identified as other important causes of external impacts for the three plant models. Radiological effects of the routine releases of the power plant on the general public are very reduced.

- ***Decommissioning and site restoration***

The decommissioning phase includes radiological decontamination of the plant and demolition of the buildings, interim storage during 50-100 years, and transport of waste to final repositories. Also included is the transport of waste to recycling plant and recycling. Site restoration to conditions as similar as possible to those before the construction is also included in the assessment.

The generated radioactive waste is assumed to be intermly stored during a period of 50-100 years at the fusion power plant site. Recycling of waste material is assumed to take

place thereafter, at a site somewhere in the EU together with a facility for manufacturing of new fusion plant components.

Radioactive components will be kept in an intermediate storage at the site from 50 to 100 years, although material might be recycled continuously, as the radioactivity of different parts become lower than the safety limit set by authorities. Non-contaminated and decontaminated materials may be taken to ordinary depositories, or recycled immediately after decommissioning. Radioactive material must be stored, and radioactive decay will with time reduce the activity of the components. The activity will thus become lower than the safety limit set by authorities. That material might then be recycled and used for other purposes. This includes segmentation, packaging and transportation to one or more recycling plants.

Two scenarios have been considered. In the first, waste is treated according to present practice, and only the not heat-generating part of the radioactive waste (intermediate level waste, ILW) is assumed to be recycled. Clearance of material has been considered if the total activity concentration is lower than 1 Bq/g at the end of the interim storage period [11].

In the second future prospective scenario, the calculations were based on criteria reported in [12]. According to these criteria, the recycling of waste material will be much more extensive than according to present practice, although mainly into new fusion power plant components. In this scenario, only 10 % of the activated material, in addition to the beryllium material, is considered to be treated as waste for final disposal.

Separate final repositories were considered, one for heat-generating waste (HLW), and another for waste with negligible thermal influence on the host rock (ILW). The former waste type was assumed to be kept in a salt formation in Gorleben. The other repository is an abandoned iron mine, Konrad, near Braunschweig.

External costs are dominated by decommissioning in both scenarios. The decommissioning phase in turn is dominated by the external costs for occupational accidents and diseases. The external cost for the future prospective scenario is somewhat larger, due to more extensive releases from recycling. This scenario was designed to reduce the volume of radioactive waste that needs to be long term disposed, however. Disregarding the occupational accidents and diseases, the external costs of the latter was larger than those found here, which means that this might compensate the higher external costs for recycling.

- ***Waste Disposal***

The use of fusion produces activated materials, which have to be disposed of when decommissioning the fusion plant. In the present study radioactive waste was assumed to be deposited in geologic repositories and the consequences of three different disposal options were examined.

Only the two most important nuclides were considered: C-14 and Nb-94. Three release cases were constructed and additionally the assumptions made in the SEAFP study were considered [8]. In the first case the release of C-14 to the geosphere was assumed to start 2×10^4 years after disposal of the material and to continue for 10^4 years. In the second case release starts after 5×10^4 years and continues also for 10^4 years. In the third case release starts after 5×10^4 and continues for 2.5×10^4 years.. In the SEAFP-study C-14 was assumed to be continuously released from the repository over a period 4×10^7 years [13]. In all cases the retention time of C14 in the geosphere was taken to be only some hundred years.

Applying generally accepted long term global dose factors, C-14 is found to be the most important activation product. If not separated very effectively from biosphere rather high collective doses and external costs can be caused due to C-14. Preliminary estimation show

that if C-14 retention can be achieved over about 2×10^4 years, the estimated external cost are 0.8 m€/kWh for plant model 1, 0.5 for plant 2 and 0.7 for plant 3, albeit with rather large error bars: 0.09-6.5, 0.06 – 4.3 and 0.08 – 5.8, for the three different cases. If retention of C-14 for 5×10^4 years could be ensured (due to an appropriate waste disposal solution) external costs from waste disposal would become ten times less for all three plant models.

• **Results**

In figure 1 the external costs estimations of the different stages of the fusion fuel cycle are shown. Total values amount for 1.61, 3.76 and 1.16 mECU/kWh for plant models 1, 2 and 3 respectively. For plant models 1 and 3, external cost are mainly due to the effect of waste disposal dominated by global exposure to C-14 and followed by occupational impacts in the construction and decommissioning of the power plant. Effects of routine radioactive emissions are very reduced even considering global dispersion of C-14 and H-3 nuclides. For plant model 2, external costs are dominated by the effect of the global dispersion of C-14, arising during the power generation phase.

In the fusion fuel cycle as a whole, global warming impacts represent only around 0.014mECU/kWh, which is a negligible contribution (less than 1%) compared with other causes of external costs.

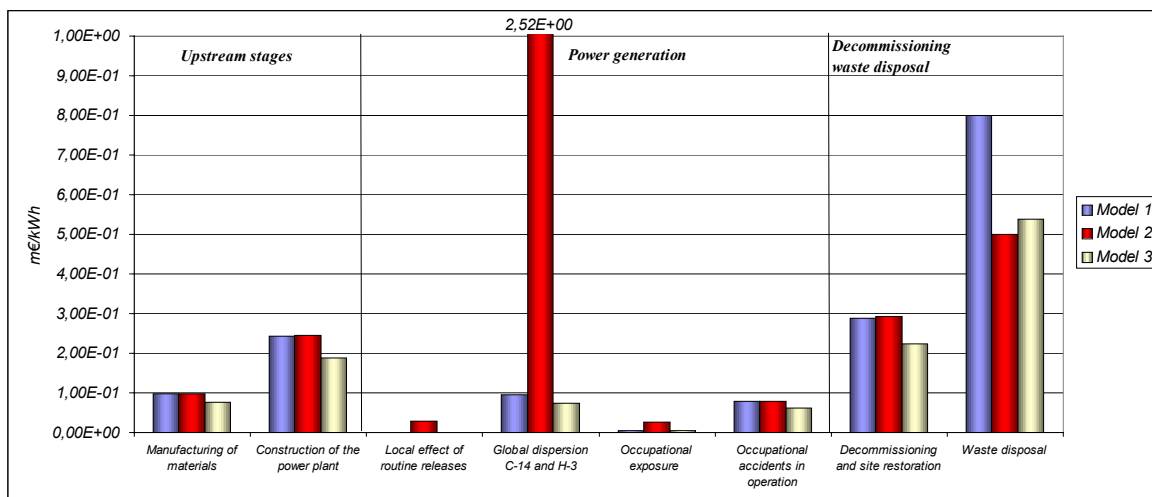


Figure 1. External costs of the fusion fuel cycle

Figure 2 shows the main components of the external costs of fusion. Note that the absolute values are small, typically less than 5% of the estimated direct costs of power generation. More than 50% of the total external costs is in all cases due to global effects of C-14. Occupational impacts are the next cause of external costs in order of importance. Together with C-14 effects account for more than 90% of the total externalities of the fusion fuel cycle. Other causes of impacts have a much lesser importance.

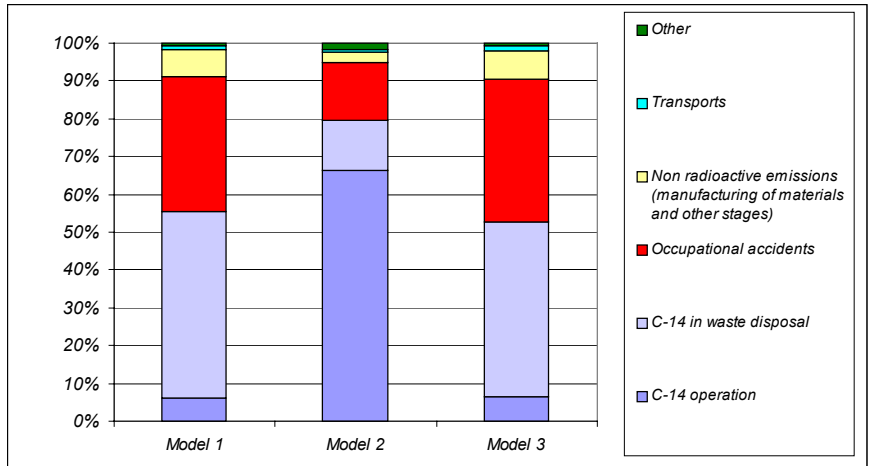


Figure 2. Contribution of different components to the external costs of fusion

3.5.3 Comparison with other energy options

External costs of fusion obtained in SERF2 are displayed together with those of other energy options obtained in the ExternE National Implementation project. The external costs for fusion have been estimated to be approximately the same as for renewable energies and lower than for fossil fuels and nuclear fission technologies as it can be observed in figure 3. All the values shown are subject to significant uncertainty. Because the external costs associated with the production of global climate change are particularly uncertain, these are displayed separately.

External costs of the various alternatives may change as new technologies are developed and costs can, to a high extent, be avoided (e.g. acidifying impacts but also global warming due to carbon dioxide emissions). Also fusion technology can experience major progress and some important external cost components probably can be avoided already by 2050. Monetization has some limitations since some aspects are often left out, and some aspects may be difficult to monetarise. Nevertheless, the assessment of external costs for different energy technologies is in principle useful as it gives a common measure for comparison.

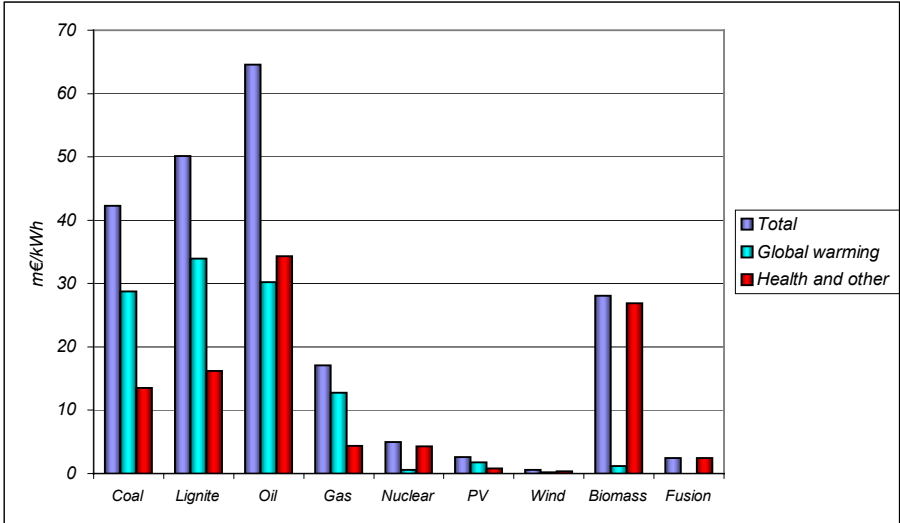


Figure 3. External costs of different energy options.

The results obtained in this comparison are not, by any means, definitive due to the reasons above mentioned. However, they could provide an indication about the position of this new technology, nuclear fusion, within the overall picture of the rest of the energy generation technologies regarding their environmental performance.

3.6 Accidents

One of the major objectives to develop fusion as a power source are the anticipated high safety standards. Even under very unlikely accident sequences there should be at no time the necessity to evacuate the nearby population. The safety reports proved that this goal could be achieved. Therefore it is to be expected that accidents are no major externality of fusion.

The accident scenario adopted here is a "beyond design basis accident" (BDBA). It is considered that a first event occurs leading to a "design basis accident" scenario, but furthermore some unlikely internal events or event combinations occur leading to a BDBA scenario. The most severe scenario considered hereafter is characterised by a major in-vessel LOCA (loss-of-coolant), followed by a radioactivity mobilisation and a failure to maintain the ultimate radioactivity confinement, and stack release. In that case, the filter efficiency is 99%, except for Tritium, for which no retention is assumed. The releases into the environment are supposed to last 60 hours.

According to the current safety analyses, the accidental situation considered refers to a release of a few tens of g of H-3. Due to the technical capabilities of the fusion power plant from the safety point of view, the occurrence of such an accident is considered to be well below 10^{-7} per year [8].

The first question concerning individual exposure in case of occurrence of an accident deals with the evacuation and/or the sheltering of the population, as well as, for longer term, the need to apply temporary relocations or permanent resettlement of the population [9]. According to the limited amount of radioactivity released in the environment in case of accident, it appears that the individual early dose for the most exposed population is significantly lower than the intervention level for evacuation as well as than the intervention level for sheltering. Furthermore, the maximum individual chronic exposure is also quite lower than the intervention levels for temporary relocation or permanent resettlement.

Although no intervention is requested in case of occurrence of the considered accident scenario, the collective exposures were assessed in the perspective of evaluating the external costs. Releases into the environment associated with such an accident lead to a cumulated collective dose integrated over 50 years of about 60 man-Sv for the local population (i.e. 100 km around the power plant), while the collective dose of the population located between 100 and 1000 km around the power plant is in the range of 130 man-Sv. In this larger area, the average individual dose is reduced about by a factor 10 compared with the average individual dose of the local population.

Generally, one of the major sensitive aspects in the case of an accident concerns the restrictions that should be imposed on food trade and consumption due to the activity concentration of the products. It should be noted that at that time, there is no regulatory derived intervention level for accidental Tritium releases. Nevertheless, for the sake of this study, such levels for the different categories of products have been derived on the basis of principles proposed by IAEA for establishing intervention levels [14]. The calculations show

that activity concentrations of Tritium may overpass the derived intervention levels, while for the other radio-nuclides (Mn-54, Fe-55 and Co-60) the activity concentrations in food products reach only the maximum of a few tens of Bq/kg, levels which may not induce significant exposure [15,16].

Given the limited amount of radioactive materials potentially released in case of occurrence of an accident, the restrictions, if any, should be rather limited to a small area (in the range of 300 km²), for a short duration (less than a week) and only for a few products (mainly milk and cow meat). According to agricultural data for the area of interest, a maximum of 800,000 L of milk is supposed to be lost, and a temporary storage of about 24 tons of cow meat is envisaged.

These conclusions on food ban, although they have to be considered with caution, are quite important as far as it appears that the reference accident scenario for fusion power plant is not severe enough to lead to significant restrictions for food trade. This element could be quite important in terms of acceptability of the situation.

For the economic valuation of the impacts, three categories of costs have been distinguished for each area: health effect costs, food ban costs, and indirect costs. For this latter, the recent developments concerning severe accidents have pointed out the need to take into account the economic consequences associated with the disturbances of the local economy [17]. Once again, in the case of a fusion power plant accident, such disturbances are rather limited. The indirect costs represent less than 5% of the direct external costs of the accident. The total external costs of the fusion power plant accident are in the range of 80 millions ECU.

The usual approach adopted for evaluating the external costs of accident consists in calculating the expected value of the cost of various accident scenarios. The main criticism of this approach is that there is a discrepancy between the social acceptability of the risk and the average monetary value required for paying compensation to each individual affected by the accident. In this paper, the risk aversion of public is integrated on the basis of recent methodological developments, relying on the expected utility approach [18].

The calculations performed for the fusion power plant accident show that the initial external costs of the accident have to be multiplied by a factor equal to 25, instead of higher values suggested in the past in the literature.

According to these different components, the external costs of the fusion accident is in the range of 10^{-5} to 10^{-4} mECU/kWh while the total external costs for fusion are estimated in the range of a few mECU/kWh.

Table 2 summarises the main results for these external costs with and without taking account of risk aversion. It should be noted that even with the integration of risk aversion, the external cost associated with accident scenario for fusion power plant still remains quite limited due to the low radiological impacts that would have to support the populations surrounding the power plant if an accident occurred.

Table 2. Total external costs and normalised external costs for an accident of fusion power plant (*Model 2 - BDBA(1) scenario - DR: annual discount rate*)

	DR = 0%
Total cost of the accident (ECU)	
Without risk aversion	4.52 E7
With risk aversion	1.22 E9
Cost of the accident per kWh (mECU/kWh)	
Without risk aversion	6.9 E-7
With risk aversion	1.9 E-5

Major accidents do not make a measurable contribution to the externalities figure. For fission accidents, which are potentially large but very improbable for plants corresponding to the state-of -the art in OCDE countries, the effect of this method of evaluation is that the calculated costs of major fission accidents are small (3.4E-03 mECU/kWh [2]). For fusion, even the consequences of an improbable major accident (probability estimated below 10^{-7} per year) are four orders of magnitude lower (in the scenario analysed here 6.9E-07 mECU/kWh).

3.7 Identification of design criteria pursuing externalities minimization

Safety and environmental performance of fusion can still be improved. Analysis of external costs is able to identify areas in which further improvement is possible and worthwhile. The reduction of external costs is a good indicator for the benefits of a design change.

This section is aimed at highlighting those areas in which the analysis of external costs suggests further improvements. A comparison with the direction taken by the European fusion R+D programme is done.

The SERF analysis already shows that the external costs of fusion are more than an order of magnitude lower than for fossil fuels, so it is not necessary to reduce the external costs to make fusion acceptable.

There are two main types of external costs: one related to conventional activities such as materials manufacturing, plant construction and dismantling; the other to more fusion specific issues such as radioactive activation of plant components. Attention is given to this later group, since it does strongly depend on the plant design and changes in the plant design can lead to considerable improvements.

3.7.1 Areas of different objectives in optimising fusion power plants

The central goal of fusion R&D was to develop a technology with no compromise in respect to the plant safety. This goal is well justified by the very strict licensing rules for nuclear installation (no evacuation necessary, in France even no counter measures) and the anticipated future rules, which might be even stricter. So even if a purely economic view would suggest making a trade off between direct and external costs, in respect to safety this will not be accepted.

3.7.2 Key issues

- **Coolant**

The most obvious conclusion of the externalities work is that power plants using water coolant are much less favourable than those that use helium. This is essentially because of the generation of C-14 in the oxygen of the cooling water, which is assumed to be released to the environment, becoming part of the carbon cycle and impacting on the global population. The implication is that rejecting water as a coolant immediately halves the external costs of fusion. Another impact of choosing helium as coolant relates to the thermodynamic efficiency of the plant. It is an important factor since the external costs are normalised to the electrical output of the plant. A more efficient plant would have higher electrical output, without increasing the external impact so the cost per kWh is reduced. The effect of this higher efficiency has been considered in plant model 3.

Fusion power plant studies so far used a very conservative estimation of the release rates, which enter as input into the present assessment. A more realistic recalculation for the water-cooled plant models, initiated as a consequence of these externalities studies, is expected to yield more favourable results.

- **Materials Selection**

The optimisation process used in the externalities assessment introduces also a new element into the material selection for a power plant.

In the material development programme of the European fusion programme, careful consideration has already been given to the potential harm of the nuclides that make up the activated structure at the end of the life of the power plant. In the externalities assessment, collective dose pathways analysis plays an important, additional role, which gives strong weight to nuclides that enter the global carbon cycle (C-14) or the water cycle (tritium). Because tritium is short lived, it is of less importance than C-14 in determining global impacts from fusion activated materials, so here we concentrate on C-14. As an example, the introduction of OPTSTAB (an optimised low activation steel) as a shield material in the European reactor design studies is partly motivated by the goal of reducing the level of activation and hazard potential in the longer term, based mainly on considerations of maximum individual doses, in order to reduce the need for repository disposal of activated materials. In the SERF programme, however, the collective doses are emphasised, where nuclides such as C-14, which becomes part of the carbon cycle, can have an impact disproportionate to their level of activation. This leads to different conclusions, for instance that OPSTAB is, e.g. worse than SS-316 in terms of external costs associated with activated materials, because its higher nitrogen content leads to a higher C-14 content (higher by a factor of 6). The necessity to give special attention to the N₂-content in the fusion material development programme, is one particular outcome of the present studies.

The following table shows a breakdown of the source of C-14 from the 3 plant models. Each column shows the fraction of the total C-14 that is generated in that material. Note that in this modelling, the shield was assumed to be made of SS-316 in each case.

Table 3. Source of C-14 from the 3 plant models.

Plant Model	Blanket Structure	Shield	Other
1	Vanadium – 20%	SS-316 – 53%	Li ₂ O – 26%
2	LAM – 60%	SS-316 – 35%	LiPb – 1.2%
3	LAM – 43%	SS-316 – 34%	Li ₄ SiO ₄ – 8.5% Be – 12%

The main sources of C-14 are the nitrogen in the steels and Vanadium alloy, and the oxygen content of the model 1 and 3 tritium breeding material. It is believed that the nitrogen in steel could be reduced, for instance to 0.01%, which would reduce the C-14 produced in steel by approximately a factor of 5. A further reduction in the C-14 production could be achieved by avoiding oxygen containing breeding materials.

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4 Long-term scenarios and the role of fusion power

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4.1 Introduction

Macro Task SE0 of SERF-1 addressed long-term scenarios. Primary aim of the task was to investigate how fusion power could fit in the group of future energy options by exploring the prospects in a systemic analysis. Fusion power is a technology with long term potential (beyond 2050) and deserves particular attention because it is a CO₂ free and virtually inexhaustible energy source. The institutes contributing to SE0 analysed this question from different angles:

ARGE Wärmetechnik (Graz, Austria) gave a detailed assessment of the economics of fusion power as an additional vector in the IIASA-WEC World Scenarios [1].

FZ Jülich focused on conventional and novel power generation technologies, which could compete with fusion power; they also examined long term scenario studies and gave ideas on the conditions for market introduction of fusion power [2].

Risø National Laboratory performed an in-depth analysis of existing long term energy scenarios, showing their similarities, differences, and possible weaknesses [3].

CEA-Lemme (Toulouse, France) examined the effects of uncertainty on the evaluation of research programmes, with special interest in the fusion programme [4].

ECN Policy Studies also analysed the main long-term energy scenarios [5], and did an in-depth analysis of the potential of fusion power in Western Europe for a number of scenarios until 2100, applying an adapted MARKAL model for Western Europe [6]. The technologies which are crucial for the evaluation of the potential of fusion power are described in [7].

The assessment of the economics of fusion power by Arge Wärmetechnik, which became available in an early stage of SERF, is the main source of cost data on fusion power. In the same way, data of FZ Jülich on conventional and novel power generation technologies that could compete with fusion power have been used. The systemic analysis was performed at ECN with a specifically adapted version of the MARKAL model for the OECD-Europe region¹ to cover the period up to 2100. This model is a technology-oriented model of the energy system that enables dynamic optimisation, producing the least-cost solution over a number of time periods and under specific circumstances (fossil fuel prices, CO₂ constraints, etc). The model was developed within the cooperative research partnership ETSAP (Energy Technology Systems Analysis Programme) under the auspices of the Internal Energy Agency

¹ The EU-15 countries, Norway, Switzerland, and Iceland.

in Paris. Today the MARKAL toolbox, which was gradually expanded with many optional features, is used by over 55 institutes in over 35 countries for a variety of purposes. At ECN, where MARKAL was used for a range of national studies from the mid eighties onwards, the database for the OECD-Europe region was developed from 1995 as part of a study on new energy and material options for the period up to 2050 [8]. Further enhancements and extensions were made for application in a comprehensive biomass potential study for the EU [9] and a study for the OECD.

MARKAL calculates a development path minimising (in a properly discounted way) the time-integrated expenditures (over the interval, and for the region considered) for energy provision. It is thus a rigorous procedure, following well-defined mathematical rules. It does require, however, in its input base-line assumptions regarding the future energy demand, and the technical and economic prospects of all technologies and primary supply sources. One can also take into account environmental constraints, by imposing limits on the total CO₂ emission budget, and the share of it allotted to Western Europe. This has been done in the ECN study. views on long-term energy scenarios.

4.2 Views on long-term energy scenarios

It seems appropriate to express some hesitation with respect to long term energy scenarios, as these are inevitably a construct of current views and expectations. However, in [3] Risø National Laboratory regards some future trends as crucial for future energy development: Population growth. The world population will grow from 6 billion people in 1999 to approximately 8 billion in 2025, ending up at some 11 billion people in 2050 and beyond. Limitations of world's fossil fuel resources, notably of oil and gas. At least conventional oil resources will peak in the first half of the 21st century.

Economic growth and growth of energy demand. It is widely assumed that GDP of the world will increase by an order of magnitude between 1990 and 2100, here a tenfold increase is assumed. The associated world energy demand would then increase by a factor 3 to 6 compared to 1990. However, this is only an estimate within a wide range.

Climate change. It is hard to assess future policies with respect to climate change, notably the balance between adaptation and mitigation. However, in light of growing consensus on climate change and the role of human activities as assessed by the IPCC, it seems a safe bet that global warming will remain an important driving force for future energy decisions.

Before developing the scenarios for the purpose of the SERF programme, the literature on existing studies with a similar scope was analysed.

The IIASA-WEC scenarios (1995) have a few common elements. Growth rates for high-income economies (OECD) decline gradually. Fossil fuels are assumed to be amply available. All scenarios envisage a gradual shift away from fossil fuel sources by the end of the 21st century. This transition may not be smooth in all cases, since the cumulative energy requirements are very large. High demands for oil and gas will require substantial technological advances in oil and gas exploration and production.

The IPCC (1996) presents five so-called LESS-variants (Low CO₂-Emitting Supply Systems). The matter of consumer interests, which is a main topic in the IIASA-WEC study, is not treated separately. Instead the consumers are assumed to be part of a society with deep CO₂ reductions on the agenda. Four variants differ in the use of sources of primary energy and a

fifth explores the options available given a higher level of energy demand. The four include a biomass intensive, a nuclear intensive, a coal intensive, and a natural gas intensive variant. The focus on deep CO₂ reductions and the consistence in demand side structures (unlike the IIASA-WEC study) give the IPCC study a more normative character than the IIASA-WEC study. In all IPCC LESS variants biomass is an important part of the renewable portfolio in the 21st century. However, unlike fossil fuels biomass is not abundant in its resource base, and land use constraints will occur at some point if energy demand continues to increase.

There are large differences in CO₂ emissions. Most scenarios show an increase from the current global level of 6 GtC, some ending up at a trebling of that level in 2100.

Considering this short overview, the following scenario categories are distinguished:

Ecologically driven scenarios. These are scenarios with intensive development in technology and a massive focus on ecology and environmental protection.

High-demand driven scenarios. Economy intensive scenarios focusing on high growth rates in global energy demand.

Ecologically driven scenarios presume that global warming will remain high on the political agenda, and that strict policies conforming to that priority will be put in place. High-demand driven scenarios focus on the most likely supply-side structures given that our capability of deploying global energy resources is pushed to the limits.

Especially consumers and policy makers can be expected to strongly affect the prospects for different energy sources. The choices made by such parties will decide to what extent the next century will be ecologically driven or high-demand driven.

Considering the various words of caution mentioned in the IIASA-WEC study - breeder reactor development, public acceptance, etc. - it seems inadequate that only one out of five scenarios foresees a troublesome future for fission energy. In the IPCC LESS variants, the opposite seems to be true: the mix of one nuclear-intensive variant and four variants with a minor contribution from fission energy suggests an ample freedom of choice from non-nuclear alternatives.

It seems worthwhile to give attention to the consequences of the scenarios for developing countries. In this framework we only mention some potential problems:

The per capita income of developing countries does not seem to keep pace with that of industrialised countries.

Even if oil and gas are relatively cheap today, it seems probable that developing countries will shift to coal as soon as oil and gas would become more expensive.

The drive for less CO₂-intensive energy sources, which is apparent in OECD countries, could be hampered by a (partial) switch to coal in developing countries.

The potential role of fusion energy is mentioned in passing in the IIASA-WEC and IPCC studies. All in all it seems worthwhile to include fusion power in long-term energy scenarios, despite uncertainties with respect to technical-economic feasibility and the long lead-time involved. If we decide to do so, it is interesting to imagine its possible impact:

Fusion power, presumed it would be technically feasible, will have more impact for OECD countries than for developing countries. However, the global scene is dynamic: for example China cannot be regarded a less developed country any longer over the time period considered.

Fusion power will be more expensive in terms of direct costs than some currently available alternatives such as fission power and coal-fired power. Therefore, fusion power - and other CO₂ free alternatives - needs some additional incentive to become a viable option. Such as carbon taxes reflecting the concerns over climate change, which are already contemplated in industrialised countries (the EU). From another perspective, such as the risk of proliferation and long-lived radioactive waste, fusion power could be favoured over fission power.

A high-demand driven scenario would at first glance seem to work in favour of energy sources with a large potential like fusion power. In a scenario with a more moderate increase in energy demand new energy sources like fusion power would face a more challenging and competitive market. However, the future level of energy demand is strongly correlated with the regional policies pursued. Sustainable energy policies are likely to induce more energy efficient and less CO₂ emitting energy structures, that can (partly) offset the rising demand of final energy. Being a CO₂ free energy source, fusion power could benefit from such sustainable policies, even in a market with a relatively 'low' level of energy demand.

4.3 Competitors to fusion power

Clearly an assessment of the prospects for fusion power cannot be made without considering what alternative options could be considered and how the various attributes of all options compare.

G. Kolb of FZ Jülich presents in his contribution to SEO [2] a number of possible competitors to fusion power. First the focus will be on fossil fuel based power and fission power, then on 'conventional' renewables, and finally on 'exotic' technologies.

The European Pressurised Water Reactor (EPR) and the Siemens Boiling Water Reactor (SWR) are advanced LWRs, characteristics of which are shown in Table 1. The option of the European Fast Reactor seems to be more disputable than the LWR. A more likely option is the High Temperature Reactor (HTR). The helium cooled HTR has outstanding safety characteristics.

Two lignite-fired power options are considered, viz. BoA-Plus and KoBra. BoA-Plus is a lignite-fired power plant with utilisation of the condensation heat of water. KoBra is the acronym for an Integrated Gasification Combined Cycle (IGCC) plant based on lignite. Investment costs (ECU 1300 and 1465/kW_e respectively) and operation and maintenance costs are comparable. Both could attain a generating efficiency of 49%.

Table 1 *Fossil fuel based and fission options as competitors to fusion power*

	Net capacity [MW _e]	Inv. Cost ² [ECU95/kW]	Oper. and maint., fixed [ECU/kW/y]	Oper. and maint., variable [mECU/kWh]	Net gen. Eff. [%]	Load factor [%]
EPR	1,450	1,900	90	0.54	34	87
SWR 1000	977	1,900	90	0.54	35	89
BoA-Plus	920	1,300	90	2.38	49	88
KoBra	1100	1,465	95	1.88	49	85
Pulv. Coal	600	1,450	80	2.10	46+	83
IGCC	823	1,415	72	1.42	49	83
Gas CC	676	580	28	0.51	60+	88
MCFC gast.	50	1,000		3.89	65	95

Also coal-fired power generation options are presented (pulverised coal fired power and IGCC). Investment costs (ECU 1450 and 1415/kW_e respectively), operation and maintenance costs, and generating efficiencies (up to 50%) are roughly comparable. A gas-fired combined cycle (CC) power plant could attain a net generating efficiency of 60% around 2000. In the near future even higher efficiencies (63%) are envisaged.

A more remote, albeit technically feasible, option is coal-fired power with CO₂ separation and geological sequestration. If CO₂ separation would be applied to IGCC, the generating efficiency would drop by 8 percentage points (from 50%) while capital costs would increase by 20-25%.

The FZ Jülich study also covers ‘conventional’ renewables. Experience with offshore wind power - actually ‘near-shore’ wind power - is scarce up to now. It is also difficult to make an assessment of the costs of solar PV and the like (solar tower). Solar and wind energy, which produce intermittent power, cannot be regarded as solitary competitors to fusion power, which is a base-load power option. Therefore, unless renewables would be so cheap that they would enable large-scale energy storage – e.g. in the form of hydrogen – in order to mitigate supply fluctuations over the seasons, some type of back-up power remains necessary. Nevertheless, renewables could have considerable impact on the potential of fusion power.

At last Kolb presents several as yet not demonstrated or even “exotic” technologies, four of which based on renewable energy:

The ‘Energy Amplifier’ (EA) concept of Carlo Rubbia.

The ‘MegaPower’ Tower.

The ‘Very Large-Scale Photovoltaic Power Generation System’ (VLS-PV).

Space-based solar power.

The Solar Energy Tower, a concept of Technion, Israel.

It is hard to imagine that none of these options will prove to be feasible, even though the specific prospects for each are highly speculative. However, not all of the ‘exotic’ renewables are appropriate for the latitude of Western Europe, viz. space-based solar power and VLS-PV.

² The ECU of year 1995 is used as reference currency in all reports considered.

The MegaPower Tower poses a relatively large technical-economic risk in case of a first-of-kind plant.

Two other important notions in this respect are availability and geopolitical dimensions. The MegaPower Tower is a base-load power option, with the restriction that the power production is not constant due to seasonal fluctuations of the temperature difference between sea level and the higher atmosphere. Space-based solar power, the Solar Energy Tower proposed by Technion, and VLS-PV would require power transmission from Northern Africa with its geopolitical dimensions.

4.4 Analysis of fusion power cost

P.V. Gilli and R. Kurz made an analysis of fusion power cost as a contribution to SEO [1]. Their focus is on cost assessment rather than on estimates of the market potential for fusion power in the 21st century.

First Gilli and Kurz give attention to the long list of publications on fusion power costs, with special attention for recent papers on ITER or ITER-like designs. Then they address the investment cost of a first-of-kind 1000 MW fusion power plant. The investment cost depends on the type of fusion reactor, ranging from ECU 10,000/kW for an ITER-like design (conservative) to ECU 4800/kW for an advanced design.

The next step is to determine a learning ratio, going from a first-of-a-kind fusion power plant to a 10th-of-a-kind plant and beyond, based on IASA-WEC learning assumptions. Gilli and Kurz make a distinction between the learning ratio of the fusion core and the Balance Of Plant (BOP). The learning ratio for BOP is lower than for the fusion core.

For successful technologies, learning is fast in the RD&D stage, i.e. cost depression is large per additionally installed power plant. After having reached a competitive cost level, learning is related to increasing numbers of (larger) identical fusion power plants rather than to major changes of the technology (Figure 1).

In the commercial stage, the major share of cost depression is due to unit size and number of units at one location. Going from 1000 MW to 1500 MW causes a cost depression of 0.794. A twin unit could show a cost depression of 0.84 compared to a single unit. Therefore, investment cost of a twin 1500 MW fusion reactor compared to a single 1000 MW unit is $0.794 \cdot 0.84 = 0.67$ (the same factor applies to a single 2000 MW fusion power plant).

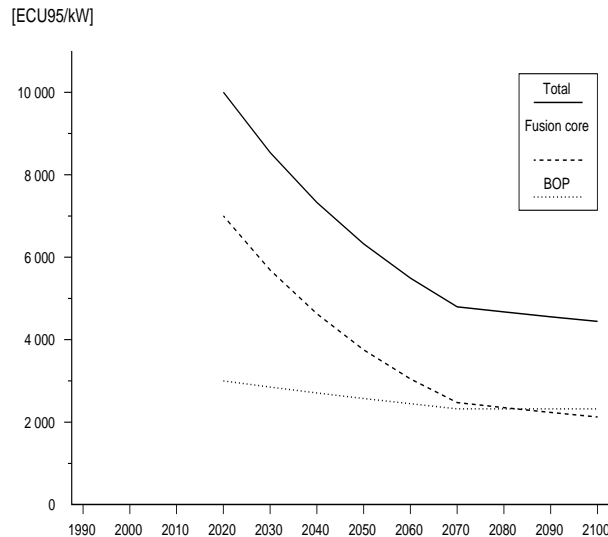


Figure 1 *Investment cost of an Nth-of-a-kind 1000 MW fusion power plant*

4.5 Long-term potential in Western Europe

ECN Policy Studies analysed the economic potential of fusion power in Western Europe with a specifically designed MARKAL model [6]. The model contains a large number of supply side and demand side technologies that can be called upon depending on their competitiveness under various conditions (fuel prices, CO₂ constraints, etc). The study has the following contents:

- methodology and scenario design,
- key input parameters of scenarios,
- two scenarios without CO₂ constraints,
- scenario variants with CO₂ policy and various discount rates,
- additional sensitivity analysis.

With respect to methodological issues the following points are highlighted:

- a) Technology assumptions are mainly based on detailed estimates, learning effects, and expert opinions included in studies of colleague institutes contributing to SERF and other studies.
- b) The issue of discounting has been solved in the following way:
 - A relatively low discount rate of 2.5% per year governs the depletion of fossil fuel resources and cumulative CO₂ emissions (if applicable).
 - A higher interest rate from 5 to 10% per year is used for energy investment decisions.
- c) Climate change is driven by the increased concentration levels of greenhouse gases. Stabilisation levels for CO₂ in the year 2100 (e.g. 450 to 750 ppm) can be translated into cumulative CO₂ emission budgets for Western Europe. This will be explained later on.

With regard to fossil fuel resources the following assumptions have been made:

- Reserve/production ratio of oil: 130 years.
- Reserve/production ratio of gas: 190 years.
- Reserve/production ratio of coal: 220 years.

- Availability of fossil fuels to Western Europe: normally 10.5% of global resources.

Price trends for imported hard coal and heavy crude oil are assumed to be as follows (Figure 2):

The price of imported hard coal rises by 0.35% per year until 2050 and stabilises after that. Prices of heavy crude oil differ for the two scenarios. *Rational Perspective* (RP), which has a low energy demand, shows an oil price ending up at \$ 25/bbl in 2100. Scenario *Market Drive* (MD), the high energy demand scenario, requires higher oil prices. After a peak in 2050, heavy crude oil ends up at \$ 29.5/bbl in 2100.

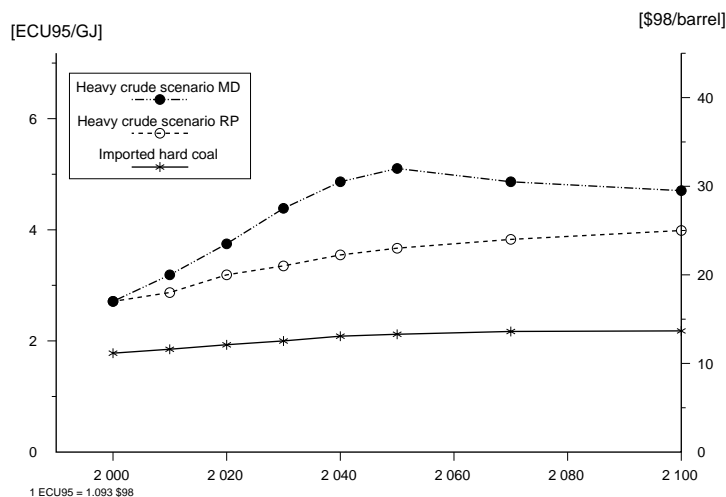


Figure 2 Heavy crude oil prices and coal price for two scenarios

Key input parameters of scenarios *Rational Perspective* and *Market Drive* are shown in Table 2.

Table 2 Key input parameters of scenarios *Rational Perspective* (RP) and *Market Drive* (MD)

	Rational Perspective (RP)	Market Drive (MD)
Decision criteria	Uniform 5% discount rate for all energy decisions across all sectors	8% discount rate for power generation; higher discount rates for end use
Energy demand	Generally lower than in MD	Generally higher than in RP
Fossil fuel available to Western Europe	10.5% of world's resources of coal, oil and natural gas	15% of world's resources of coal, oil and natural gas
Energy prices	Oil price increases slowly until 2100; \$ 25/bbl in 2100	Oil price increases faster, peaking in 2050; \$ 29.5/bbl in 2100
Fission energy	Maximum capacity declining to 70% of current capacity and 40 GW in 2100	Maximum capacity declining to 80% of current capacity and 40 GW in 2100

Note that fission energy is assumed to decline to 70-80% of its current capacity in 2070 and to one third of its current capacity in 2100. This is how a technology with particular problems with regard to public acceptance may be constrained (or not, as will be shown in the sensitivity cases).

Rational Perspective is the ecologically driven scenario. The process of global economic integration will lead to more collective public action in this scenario. International co-operation will be more efficient in order to deal with complex shared problems. Heavy polluters and energy intensive industries will decline in comparison to more environmentally friendly sectors like services. Strong penetration of new, more efficient demand and supply technologies is facilitated.

In the ‘high growth’ scenario *Market Drive*, the market mechanism is seen as the best way to produce wealth and handle complexity in uncertainty. The penetration of more efficient demand and supply technologies totally depends on market forces and the behaviour of the actors. Energy policy is driven by the desire to maximise efficient operation of free markets. Barriers will persist in the uptake of efficient equipment. Efficiency gains will only be made for competitive reasons.

CO₂ emission in Western Europe would increase by 20% (scenario *Rational Perspective*) to 60% (scenario *Market Drive*) in 2100 compared to 1990. This summary focuses on the power generation mix, e.g. the base-case of scenario RP (the case without CO₂ constraint, Figure 3).

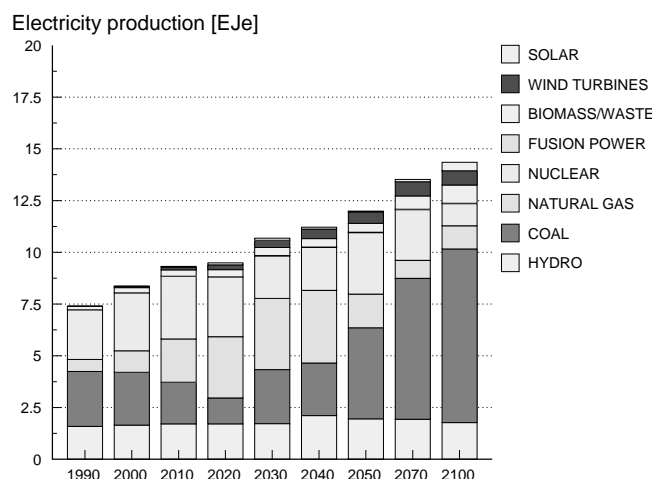


Figure 3 Power generation by source for scenario *Rational Perspective* without CO₂ constraint

MARKAL calculations show that fossil fuels are favoured for power generation in the absence of CO₂ policies. In scenario RP, gas-fired power grows strongly until 2040, after which coal gets a competitive edge. Fission energy declines slowly until 2040. After that, a revival of nuclear energy occurs. Because of ongoing technological development, some renewable power generation options, particularly onshore wind and biomass, become more or less competitive without CO₂ policies. However, other renewables – offshore wind, PV – and fusion power cannot compete with conventional power generation options in the absence of such policies.

Figure 4 shows the power generation mix of the base case of scenario *Market Drive*.

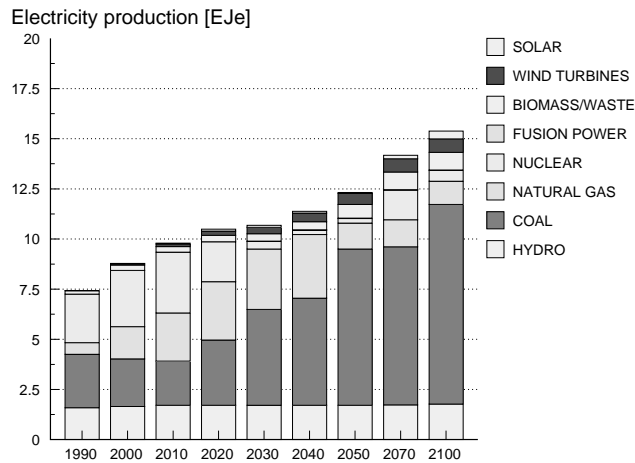


Figure 4 *Power generation by source for scenario Market Drive without CO₂ constraint*

In scenario MD, coal-fired power remains stable until 2020. After that, coal becomes more and more dominant due to relatively high gas prices. Fission energy shows a steep decline towards 2030, and it recovers not earlier than in 2070 because of the relatively high discount rate of scenario MD. Just like in case of scenario RP, onshore wind and biomass are more or less competitive, whereas other renewables and fusion power cannot compete without CO₂ policies.

The potential of fusion power has also been analysed under conditions of constrained CO₂ emission. The pre-industrial atmospheric CO₂ content was 280 ppm. The current atmospheric CO₂ content (1999) is 367 ppm. The IPCC has calculated global CO₂ emission budgets for the period 1990-2100, corresponding to atmospheric CO₂ levels from 450 to 750 ppm in 2100. As the emission share of Western Europe in IPCC's 1992 scenarios proved to be 10% on average, this percentage has been used for Western Europe's share in IPPC's cumulative CO₂ budgets. Figure 5 shows the patterns of CO₂ emissions corresponding to scenario *Rational Perspective* and variants from 450 to 550 ppm in 2100. Similar patterns emerge in case of scenario MD.

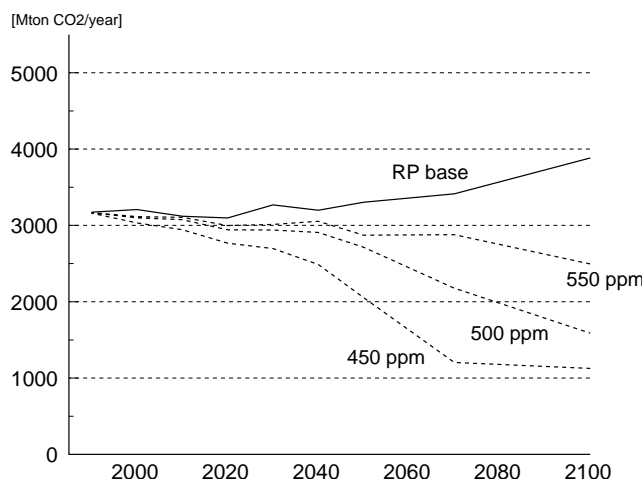


Figure 5 *Western European CO₂ emissions, variants scenario Rational Perspective*

Figure 6 and 7 show the impacts of increasing CO₂ constraints for the power generation mix in the year 2100 in case of the scenarios Rational Perspective and Market Drive respectively.

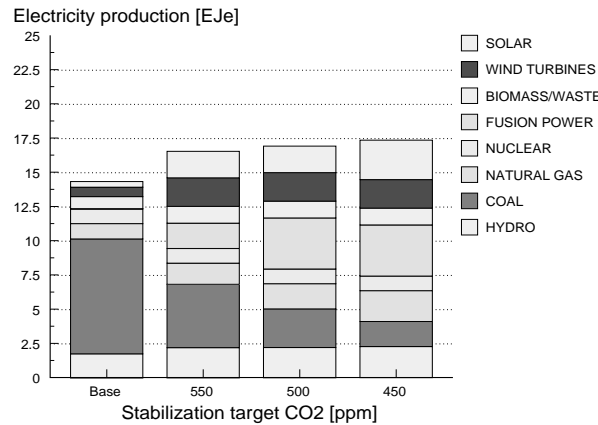


Figure 6 Power generation by source in 2100, CO₂ variants of scenario Rational Perspective

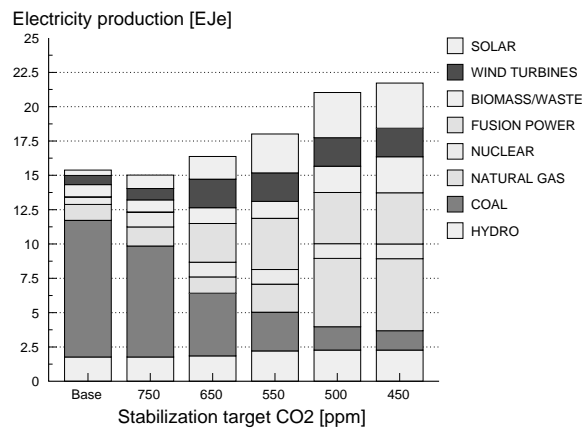


Figure 7 Power generation by source in 2100, CO₂ variants scenario of Market Drive

The MARKAL model contains options to conserve electricity and options to substitute electricity for gas (electric heat pump) or oil (electric car). The demand for electricity increases under demanding CO₂ constraints, as the potential for electricity conservation is depleted.

MARKAL optimisations show that fusion power is maximised at a level of 500 ppm in scenario RP, at the expense of coal-fired power. Fusion power is compatible with renewables like wind and PV. It is the least-cost optimisation within MARKAL which determines their market shares.

According to the MARKAL optimisations, fusion power is maximised at a CO₂ level of 550 ppm in scenario MD, at the expense of coal-fired power. Scenario MD is more demanding from the point of view of CO₂ reduction. Gas fired-power gets a boost in the more ambitious CO₂ reduction cases (500 and 450 ppm), because fusion power is already at its upper limit. Note that a default maximum introduction path for fusion power has been imposed from 2050 to 2100.

Figure 8 shows the power generation mix of a variant of scenario *Market Drive* with a large potential for fission power, viz. 200 GW (an increase of 60% compared to its current capacity).

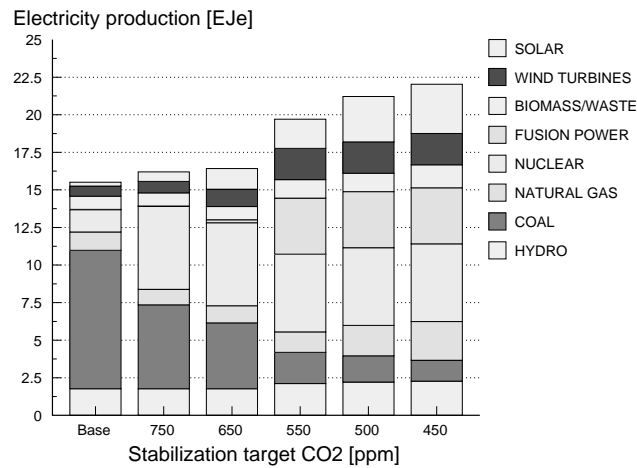


Figure 8 Power generation by source in 2100, MD variant ‘High Potential Fission’

In this case, which is highly optimistic with regard to fission power, fusion power remains economically viable in case of CO₂ reduction, although its market share is really small in the 650 ppm case. As a matter of fact, in this particular case the marginal CO₂ reduction cost is ECU 67/tCO₂, which is about twice the ‘normal’ level of some ECU 30/t CO₂.

In order to exclude potential pitfalls, sensitivity analysis has been for a number of cases, viz.:

Scenario RP with discount rate 8% (the set of discount rates of scenario MD).

Scenario RP with discount rate 10%.

Scenario RP with phase-out of fission energy.

Scenario RP with high availability of fossil fuels (15% of global resources, like MD).

Scenario MD with discount rate 5% (like in scenario RP).

Scenario MD with high investment cost of fusion power.

Scenario MD with a high potential of renewable energy.

Scenario MD with a high upper limit for fission energy (200 GW).

Table 3 and 4 show fusion power capacity for the ‘normal’ scenario variants and for the sensitivity cases for the years 2070 and 2100 respectively.

Table 3 Installed fusion power, CO₂ variants and sensitivity cases, year 2070 [GW]

Scenario	Case	650 ppm	550 ppm	500 ppm	450 ppm
RP		×		12.8	57.4
RP	Disc. Rate 8%	×		12.8	57.4
RP	Disc. Rate 10%	×	9.5	47.6	58.9
RP	Phase out of fission	×	1.9	12.8	57.4
RP	High Fossil Fuel Avail.	×		1.9	57.4
MD		1.9	47.8	57.4	58.9
MD	Disc. Rate 5%		12.8	57.4	58.9
MD	High cost fusion		37.0	57.4	58.9
MD	High Potent. Renew.			1.9	12.8
MD	High Potential Fission		12.8	57.4	58.9

1 × means the unconstrained RP scenario is roughly comparable with the 650 ppm level.

Table 4 *Installed fusion power, CO₂ variants and sensitivity cases, year 2100 [GW]*

Scenario	Case	650 ppm	550 ppm	500 ppm	450 ppm
RP		×	78.4	157.5	157.5
RP	Disc. Rate 8%	×	102.3	157.5	157.5
RP	Disc. Rate 10%	×	140.3	157.5	157.5
RP	Phase out of fission	×	119.3	157.5	157.5
RP	High Fossil Fuel Avail.	×		119.3	157.5
MD		119.3	157.5	157.5	157.5
MD	Disc. Rate 5%	69.8	157.5	157.5	157.5
MD	High cost fusion	56.5	157.5	157.5	157.5
MD	High Potent. Renew.		83.0	119.3	157.5
MD	High Potential Fission	8.3	157.5	157.5	157.5

1 × means the unconstrained RP scenario is roughly comparable with the 650 ppm level.

The main results from the scenario variants and sensitivity cases are as follows:

Scenario MD is more demanding from the point of view of CO₂ reduction than RP. So, fusion power is more important at moderate CO₂ emission levels in case of MD.

If the discount rates of scenario MD (8% discount rate for power generation) are substituted for the 5% discount rate of RP, fusion power capacity rises to 102 GW in 2100 in the 550 ppm case of RP (instead of 78 GW). This is because some renewables – notably PV at northern latitudes – have a higher capital cost component in their generation cost than fusion power, although the latter has high replacement cost (diverter, blanket, first wall).

A 20% higher level of investment costs for fusion power does not have a decisive impact on competitiveness. In the 650 ppm CO₂ reduction case of MD, fusion power capacity in 2100 is 119 GW; 20% higher investment costs cause a decline to 56 GW.

If scenario RP is combined with ample availability of fossil fuels, fusion power loses competition with gas-fired power in the 550 ppm CO₂ reduction case. However, it remains an economically viable option at 500 and 450 ppm.

If a high potential of renewables is assumed for MD, fusion power loses market share in the 550 and 500 ppm CO₂ reduction cases. However, a high potential of renewables is more threatening to coal- and gas-fired power than to fusion power.

Under alternative conditions that are deemed plausible, fusion power is rather insensitive to the fate of fission power. In case of an early phase-out of fission energy, fusion energy takes over its market share in 2100 in the 550 ppm case. In case of a steep growth of fission energy (from 125 GW today to 200 GW), fusion energy suffers only in the 650 ppm case.

Another set of calculations concerns variants in which fusion power is unavailable. Equal CO₂ stabilisation levels can be attained, albeit at a (substantially) higher cost. As the CO₂ bound is a cumulative constraint, deeper CO₂ reductions in the first half of the 21st century (when fusion power is unavailable anyhow) would provide natural gas for gas-fired power as a substitute for fusion power. Increased use of renewables only gives relief under moderate CO₂ constraints.

In the MD scenario the total, discounted cost associated with 550 ppm increases from 810 to 900 billion ECU. In the 450 ppm case, the total discounted costs increase from around 3900 to 4700 billion ECU. The difference, viz. 90 billion ECU and 800 billion ECU respectively, constitutes the discounted shadow value of the fusion power option available to Western

Europe in the 21st century (not counting the value for the rest of the world and for the next centuries).

Finally, the potential of fusion power under various conditions from the MARKAL optimisations is compared to the global potential estimated by Gilli and Kurz [1] in Figure 9.

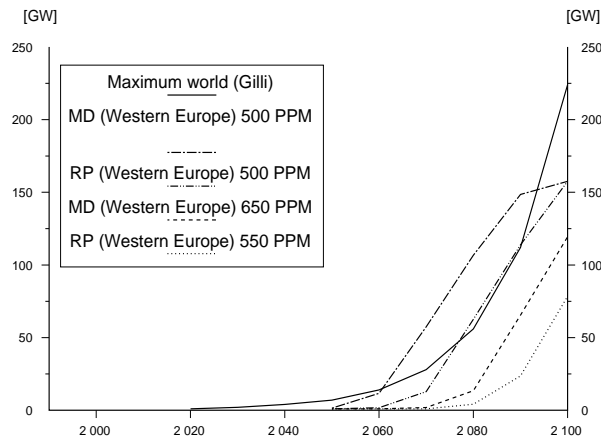


Figure 9 *Fusion power in Western Europe and in the World*

Figure 9 shows that the capacities from the MARKAL calculations are not excessive compared to the global potential calculated by Gilli and Kurz for 2100. Indeed, their curve may be even somewhat conservative for the period 2050-2070 in case of CO₂ reduction policies.

4.6 Conclusions

Long term energy scenarios including fusion power were not available before the European Commission (DG XII) started the SERF programme. Fusion power has largely been neglected in long-term energy scenarios because: Fusion power will not become commercially available before 2050. It has to be demonstrated that fusion power is technically feasible.

A distinction is made between ecologically driven and high-demand driven scenarios. If scenarios cover the entire 21st century, fusion power can be included because it is a CO₂ free and virtually inexhaustible power generation option.

Base-load power options like coal-fired power and fission power (LWR) are economically viable competitors to fusion power in the second half of the 21st century. Intermittent renewables – solar power, wind energy – are gaining importance. Although they could have considerable impact on the potential of fusion power, they cannot be regarded as solitary competitors to fusion power, which is a base-load power option.

Not demonstrated, or even ‘exotic’ concepts, are the ‘Energy Amplifier’ concept of Carlo Rubbia (a combination of a particle accelerator and a U²³³ breeder reactor, using Thorium as fuel), the ‘MegaPower’ Tower (using the temperature difference between sea level and at great height), space-based solar power, and the Solar Energy Tower proposed by Technion in Israel for desert regions on both sides of the equator (using a downdraft of air cooled by a spray of sea water at the top of a 1200 m high tower to generate power at the base of the 400 m diameter shaft). None of these concepts can be developed in short course. However, they promise globally or regionally a pronounced contribution to the electricity supply, presumed they would be technically feasible.

The investment cost of fusion power can be estimated, starting with first-of-a-kind fusion reactors (ITER-derived) and estimating the effects of technical improvement (including larger unit size and multiple units at one site) and increasing numbers of plants. Between 2030 (DEMO, the successor of ITER) and 2050 electricity production by fusion power is in the demonstration stage, and costs could come down rapidly. After 2050 cost depression is largely linked with increased numbers of plants: costs will come down slowly.

Investment cost of a twin 1500 MW fusion power plant is estimated at ECU 3000/kW (ECUs of year 1995) in 2100. Power generation costs could be 68 mECU/kWh for a commercial 1000 MW fusion power plant (discount rate 5%). Such costs come up from an independent cost estimate made at the start of the SERF programme. Power plant studies conducted later came to somewhat higher estimates, which were included in the sensitivity analysis of the ECN study.

The long term potential of fusion power depends on the priority of climate change policies. As fusion power is rather costly, it cannot compete with alternative base-load power options in the absence of CO₂ policies. However, it seems a safe bet that global warming will remain high on the agenda. Therefore, fusion power would be an economically viable option if climate change remains a dominant issue. Scenario calculations with an updated MARKAL model for Western Europe (1990-2100) show that coal-fired power is notably favoured in absence of CO₂ policies. CO₂ emission in Western Europe would increase by 20 or 60% in 2100 compared to 1990.

In case of CO₂ constraints, fusion power starts to become competitive at shadow prices ranging from 30 to 70 ECU/tCO₂. In a scenario with relatively low energy demand, fusion power obtains a share in power generation in 2100 that is slightly higher than the share of fission power, if global stabilisation of CO₂ at 550 ppm would be needed (slightly decreasing CO₂ emission in Western Europe). In both main scenarios, fission power is assumed to decrease to 40 GW in 2100 (one third of its current level) due to presumed problems with public acceptance.

In case of a 'high-demand' driven scenario, fusion power obtains a substantial share in power generation in 2100, viz. 119 GW, if stabilisation of atmospheric CO₂ at 650 ppm is aimed at. In order to reach such a level, fusion power is already introduced in 2070. Fusion power mainly competes with coal-fired power.

Sensitivity analysis shows that higher discount rates (8 or 10%) are not detrimental to fusion power, assuming fusion power has some market share due to CO₂ constraints in case of a 5% discount rate. This is because some renewable power options - notably photovoltaic power in the northern part of Western Europe - have a higher capital cost component in their generation costs than fusion power. A case with 20% higher investment cost of fusion power does not show much difference with the case with the above-mentioned cost level of ECU 3,000/kW.

Fusion power would face competition from gas-fired power in case of ample availability of fossil fuels (15% of global resources available to Western Europe) and an ecologically driven scenario. This case shows that availability of oil and gas affects the competitiveness of fusion power to a certain extent. If a high potential for renewables were assumed, fusion power would lose market share under moderate CO₂ reduction conditions. However, a high potential of renewables is more threatening to coal- and gas-fired power than to fusion power.

If a complete phase-out of fission power in 2080 is presumed, fusion power could profit somewhat in a moderate CO₂ reduction case. If fission power is allowed to grow (from 125

GW up to 200 GW), fusion power is less prominent in the 650 ppm CO₂ reduction case (of the high-demand driven scenario).

Within the time horizon of the year 2100, equal CO₂ stabilisation levels can be attained, albeit at a higher cost, if fusion power is assumed not to be available. The benefits of fusion power depend on the level of CO₂ stabilisation aimed at, just like the economic potential of fusion power and on the level of energy demand of a scenario. In the high demand scenario MD the total discounted cost to meet the 550 ppm target rises from 810 to 900 billion ECU. The gap widens with lower stabilization levels: for 450 ppm the discounted cost rises from 3900 to 4700 billion ECU. In case of a scenario with low energy demand like RP and/or moderate CO₂ reduction levels the benefits of fusion power are relatively small.

It has been demonstrated in the IIASA-WEC study of 1995 (and in other studies as well) that the rising CO₂ concentration of the atmosphere is not a short-term but a long-term global problem (of the second half of the 21st century and even the 22nd century). It therefore requires - in addition to the better-known short-term efforts - long-term solutions. As far as base-load power generation is concerned, such solutions should be based on CO₂ free, practically unlimited primary energy sources. Not many of such options are available. Presumed that fusion power is technically feasible, it would probably be one of the few options available.

4.7 References

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5 Social Acceptability of Fusion

A number of SERF projects addressed the sociological aspects of fusion as a large technical system, and the public attitude towards research in this field and its ultimately practical incarnation in the form of fusion power plants.

The following authors and institutes contributed to these studies:

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It was recognized early on by the participants in this study that fusion is not yet a matter of public debate, so that the opinion towards the *ongoing process of fusion R&D* or the opinion towards the *construction of the ITER experiment* should therefore form the primary object of sociological research.

The temporary consideration of Porto Torres as a candidate site for ITER allowed conducting a realistic field test in the area of public attitude formation.

5.1 Local communities and large experimental fusion facilities: the awareness process at Porto Torres

In 1997 the Italian government offered to host ITER, the International Thermonuclear Experimental Reactor designed to demonstrate the technological feasibility of producing electricity through fusion. Besides the difficulty of gathering the financial support to the project, a more national specific problem had to be solved: after the Chernobyl accident and the abandonment of the nuclear energy option, the Italian population has been opposed to discuss any sort of nuclear related activity.

The implementation of a project has to deal effectively with the territory it concerns in order to minimise social as well as economic costs. Resistance by local population is most probably going to inflate costs and eventually force to change the initial plans. Therefore the site of any large-scale installation decision cannot be decided without taking into consideration the social, economical and cultural characteristics of the local community. Even before informing the population about the project, one has to establish a common language and mutual trust.

With this in mind, ENEA, the Italian Agency for New Technologies, Energy and Environment, offered to verify under which conditions a local community would have been ready to host a large fusion demonstration facility. Among the reasons supporting the choice of Porto Torres (province of Sassari, in Sardinia) are: the location was among the few candidate sites selected by a governmental commission, it needed a new economic development, it is well characterised from the statistical point of view, the mayor showed an open attitude, the insularity enhances the effects, and the nearby university of Sassari has a strong social sciences team.

5.1.1 Possible socio - economic impacts of installing a large fusion demonstration facility in Porto Torres (SERF1)

At the start of the project the urban reality of Porto Torres (province of Sassari, in the island of Sardinia) was studied in order to monitor the characteristics of the territory, to assess the patterns of communication and of participation to decision processes. With the support of the local authorities, making use of appropriate *methodologies*, the following characteristics were analysed: economic status and social dynamics of the territory from 1951 –1997; territorial use and planning based on documents of the local authorities; urban culture via an anthropological analysis; reporting on environment, industry and technology in the local newspaper (La Nuova Sardegna); events from the period of the first industrialisation to future projects as emerging from interviews with local opinion leaders and citizens.

Porto Torres is a small town of 22.500 inhabitants, a port placed in the North West of Sardinia. Starting from the '60s up to the '80s the town has been interested by a strong process of industrialisation, mainly in the base chemicals sector. The decommissioning of most base chemical plants in the early nineties led to a high unemployment rate (nearly 25% in 1991 against a national average of 12%). The environmental conditions of the area had been strongly modified and got worse as a consequence of the installation of the base chemicals factories. Tourism, which presently is the main economic activity of Sardinia, cannot compensate for the failure of the industrialisation process in Porto Torres.

Several major projects are currently discussed for this area: the installation of a new coal power plant integrating an already existing oil power plant, the creation of a National Park on the island of Asinara, and the installation of a liquefied natural gasification plant in the harbour. These projects meet partly strong opposition (coal plant), and partly enjoy strong support (National Park). The public attitude towards the gasification plant is not yet well defined, mainly because of lack of information. The analysis of the local press showed no inherent opposition to the use of new and existing technologies, but a strong concern with their environmental performance. With regard to the *public participation* in these projects, it turned out that the local population had never been informed on nor involved in the decisional processes concerning them. Most decisions have been taken at a high level, often by national government officers. A sense of mistrust towards institutions and new proposals or hypotheses developed locally. This attitude was confirmed through in depth non-structured interviews with key informants about Porto Torres in general and about their perception of risk and of new technologies.

After learning about the local social dynamics the team started to inform the local community about the ITER project. In agreement with the mayor of the city most *local associations* were

invited to discuss the technical and economic content of the projects in public hearings. The local organisations were invited separately, according to their main objectives:

High schools

Political parties and labour unions

Association of agriculture, industry, commerce and service producers and craftsmen;

Cultural associations and school operators

Voluntary service associations

Sport club associations.

The degree of participation among the 120 and more invited citizens was rather low. Fusion was presented to the local audience through a package of slides dealing with the following topics:

Why we speak about fusion

How it works

What is the state of the research

How it is done

Safety aspects

Environmental aspects

Social and economic aspects

The *economic implications* of such an installation for the local community and the regional economy were assessed separately in great detail, addressing both the direct activation of the local economy (contracts locally placed for providing components, infrastructures, supplies, services, etc., as well as local expenditure of the personnel working and living at the site) and the indirect activation expected due to the boosting of many economic sectors induced by the direct activation. In total, the sum of direct and indirect activation was estimated to amount to 34% of the total construction costs of ITER.

After public hearings were over, in accordance with the local administration, the team proposed to the local community a structured one-day discussion on “Strategies for local development” based on the European Awareness Scenario Workshop (EASW) concept. This methodology had been developed in the early nineties by the European Commission to increasing the conscious participation of local communities to the choices associated with science and technology. In this workshop, the community was asked to develop guidelines and scenarios for a general development strategy, striking, in particular on a balance between low and high-tech, and between collective and individual solutions. The discussion proceeded in different stages, within groups initially formed to represent different aspects of the community (resident citizens, politicians, technology experts, entrepreneurs), but reshuffled during later stages. The attitude was generally positive towards new technologies. Having been strongly affected by previous monocultural development experiences, all groups propose scenarios that take into consideration more than one source of wealth for their community. All groups emphasised waste recycling and related new technologies and suggested to promote the local environment and archaeological sites in order to improve the tourism economy. In stages the individual groups developed concrete proposals, which were then voted upon by them in a plenary session.

At the completion of the first phase of the social awareness process, the social methodology used in Porto Torres had proven to be very effective. At least four important issues emerged from the research:

- the populations expressed a strong need for participation in local decision making;
- development strategies have to be based upon composite visions;
- with the support of the local actors in stimulating and managing the participation processes (the university and the local administration - in the person of the mayor, in particular) it is possible to establish a local network and to develop the thrust necessary to start an awareness process;
- the participants to the workshop, chosen according to their role in the local community, perceived the importance of their participation, worked hard, and were at the end ready to become important partners in the public awareness process.

The EASW process demonstrated the open attitude of the local population towards new technologies and – in contrast to the situation at the onset the project - the willingness to learn more about the technological aspects of large fusion demonstration facilities, and the social, economic and environmental implications of such an installation. In this first phase, however, the process could not arrive at a point ensuring the full acceptance of the project as a way towards local development. Basically more time was needed to diffuse full information, to deepen the knowledge, and to discuss and understand the implications.

5.1.2 Porto Torres confronted with the experience of Culham – JET (SERF2)

The second phase of the Porto Torres project, conducted under SERF2, had three main objectives:

- to complete the participation process started in phase one, by adopting the same methodology that had proven to be successful;
- to focus the participation processes more specifically on the topic of fusion, in order to get specific answers to its social, cultural, economic and environmental acceptability;
- to identify better strategies of local development compatible with the installation of a large fusion demonstration facility. The previous phase had demonstrated that such an installation is more acceptable if composite (instead of monocultural) development perspectives are proposed to the local population: fusion has better chances to be accepted if it is proposed within et-et instead of aut-aut solutions.

Having shown the readiness of the local community to develop their town with the help of high tech, it had to be determined under which conditions this development could go along with the installation of a large experimental facility. The SERF2 project developed through three steps:

a comparison of the socio economic situation of Porto Torres with Culham (UK), where the JET laboratory is operational since 1983 (“indirect approach”) a visit of a delegation of citizens of Porto Torres to the JET laboratory and their meeting with representatives of the local community in Culham (UK) (“direct experiences”); the participation of representatives of the local communities of Porto Torres in a Strategic Scenario Workshop: in this adaptation of the EASW to the new local conditions, citizens discuss possible local future development scenarios with or without the construction of a large fusion demonstration facility and become aware of the consequences of either choice.

The analysis of the present situation of the two environments and the study of the model of Culham was concluded with the organisation of a social laboratory in the UK. A group of Porto Torres citizens participated and verified directly the effects of the model of development started at Oxfordshire and the role of the research centre. The technical-scientific content of the Research Centre was widely explained, as was the socio-economic environment of the local communities.

The main objectives of the visit were to let the participants: acquire knowledge on the technology of nuclear fusion and on the ongoing experiments, through a direct and unusual contact with the experts; verify directly the impacts of the JET installation on the surrounding territory, the consequences for the environment, the degree of social acceptance, the direct and induced development of the local economy; hear directly from the technical staff of JET and local administrators of Culham answers to problems and questions related to the acceptance and safety of a high technology plant; diffuse the information and open an informed discussion in the local community of Porto Torres;

During the visit moments of direct observation alternated with meetings with local agents and short illustrative seminars held in the research centre. Concerning the technology of thermonuclear fusion, evidence was given of the differences to nuclear fission, mainly in terms of safety and risk. The technical explanations given by scientists and managers of the research centre alternated with moments in which participants could present their problems and questions.

The reports of the visit drafted by the seven Porto Torres representatives after their return home were all positive. The change in attitude before and after the visit was evident: the original doubts were substituted by the general feeling that the installation in Porto Torres of a similar facility would not be risky and might bring to the area large socio-economic benefits.

A Strategic Scenario Workshop (a methodological adaptation of the EASW) was subsequently organized, designed to help defining the parameters of acceptance of nuclear fusion facility and of a research centre. Two scenarios were presented to the participants, corresponding to the development of the local area with and without the large fusion demonstration facility. In particular this methodology has allowed creating a reference scenario and to point out the development of a project recalling possible risks, barriers, succeeding factors, additional targets and other qualifications for future strategies. The reference scenario has really helped the participants to assess the socio-economic impact of the Research Centre related to a possible local development.

The presence and participation in this phase was higher than in SERF 1, both at the public hearings and at the final awareness workshops. This increase of common people participation is definitely linked to a deeper awareness in the whole local community. The Strategic Scenario Workshop "Porto Torres 2005: realisation of a research centre on fusion" was attended by almost 50 participants, chosen by the local Administration of Porto Torres and the staff, mainly among young people and students.

As to the final identification of the acceptance factors for ITER in Porto Torres the environmental compatibility seems to be the most important element to accept the project. The second important factor is information and communication, which must be large, complete and continuous. Economic factors follow are ranked third; they indicate that the implementation of the project must improve the local economic development. Although for other general reasons the Italian government at the end had to repeal the Italian candidacy to host ITER, the socio-economic study demonstrated that through an appropriate awareness and

public participation process it is possible to find the condition to gain public support to the installation of such large facilities.

5.2 Fusion in the public opinion

Further research in the public opinion on fusion involved field studies in the form of focus groups and of interviews with selected groups, as well as literature studies and assessments based on the experience from other large, high-tech projects.

As mentioned above, the general know-how on fusion is poor, so that meaningful empirical studies either require a careful and detailed introduction into the subject, or have to restrict themselves to sections of the population with an above-average starting knowledge. In both cases, great care is needed to avoid introducing a bias.

A Spanish group, constituted by researchers of CIEMAT and the University Complutense held semi-structures interviews with fission and fusion experts, science journalist, and representatives of environmental movements and of the organisation for the defence of nature. Participants were asked of their opinion on: envisaged benefits and drawbacks of fusion compared to other energy sources, fusion as commercial reality, funding of fusion research, social acceptability, perception of risks.

Fusion was generally seen as an unlimited source of energy (only fission experts put less emphasis on this point), albeit associated with high costs. Risks were perceived mainly from tritium leaks and generated waste, but were estimated lower than in the fission case. All groups appreciated a diversified energy supply system, but had different ideas about the distribution of weights. Environmentalists favoured models largely based on renewables; the fission expert preferred those based on fission, while journalists and fusion experts favoured a balance of fusion, fission and renewables. All groups saw still numerous technical problems to be solved for fusion to become a commercial reality.

The Max-Planck-Institut für Plasmaphysik (IPP) and the Akademie für Technikfolgenabschätzung in Baden-Württemberg (AFTA), Germany, tested the method of focus groups to gain information on attitudes towards fusion. Focus group discussions always proceed in two stages: an introduction to supply the stimulus and a moderated group discussion to measure the opinion formed in reaction to the stimulus. Each focus group consisted of six to eight persons. Groups were selected to represent a broad spectrum of social and cultural backgrounds: managers, young people (ages 15 to 18), science journalists, environmentalists, cultural elite, and science teachers. To minimize bias, two introductory statements on fusion were given: one by IPP which is conducting fusion research, the other by Öko-Institut Darmstadt, which plays a central role in German debates on nuclear safety issues, and is known as being very critical towards nuclear technologies.

In all groups the following topics arose in the discussion: cost/benefit ratio of fusion research, future lifestyle, risk, differentiation between fusion and fission energy, credibility of experts. The final discussion was introduced by the question: "Fusion as an energy option - yes or no?" The groups of environmentalists and science teachers rejected fusion as an option for future energy supply, and also the cultural elite tended to oppose it. Science journalists held an ambivalent opinion. The group of young people favoured fusion, an attitude, which was even more pronounced in the group of managers and engineers. All but two groups started from the

tacit assumption that the amount of money spent for energy research was a fixed quantity, which had to be shared by the various technologies. The risk debate, which generally governs discussions on fission, was less emphasised here. The scepticism towards fusion was primarily motivated by the strong preference for alternative energy sources. Optimism was motivated by the view of fusion as an option for future generations. Fusion research should be upheld at least until the feasibility of a fusion power station is proven. None of the groups recommended stopping fusion research immediately.

The Institute of Risk Research (Univ. Vienna) conducted literature studies to identify general criteria, which are important in the process of public opinion formation. Within this effort, researchers analysed the history of the liquid fast breeder reactor development, and the causes for its failure to obtain public support. Cited as contributing elements were the sensitivity of the public to plutonium, the loss of interest of industry during the process due to lack of a clear-cut economic perspective, the absence of an independent, knowledgeable regulatory body (the regional authorities were not able to handle the breeder project properly), and the failure to install in time a proper technical licensing frame. The study warned also of a misunderstanding of the public perception of risk by the scientific community. The authors of the study consider risk perception to be relatively immune to scientific evidence, and claim that attempts to educate the public on how to perceive a risk will fail.

In SERF2 this group made a scoping assessment of regulatory requirements for fusion power stations, support systems and equipment, and produced an overview on methods in safety assessment and for formulating safety criteria for nuclear facilities and for process industries with hazardous materials (Seveso II plants). In particular they highlighted the relevance of the Seveso Directive as a framework requiring an integrated risk management programme that can build trust among the stakeholders. In addition to the obligation to inform the public about major industrial risks and all accidents, the Seveso II Directive obligates the industry and authorities to consult the public on matters pertaining to emergency response and land-use planning.

5.3 Fusion as a large technical system

As a research enterprise, fusion is extreme in many aspects. Three characteristics, which set it apart are: the long time horizon, the broad international coordination and the dependence on large research facilities. The conclusive step in the demonstration of the physics feasibility of fusion – the quasi-steady operation of predominantly self-heated plasma – can happen only in a very large device. The fusion community, which has since a long time an outstanding record of worldwide cooperation, is about to concentrate its global effort in the construction of a single experiment of this kind. ITER is a mega science project and prime example of globalised research. Fusion research, and the way in which it is conducted, is therefore by itself also a fascinating object of research. Within the SERF frame, three groups addressed these aspects and the related question of governance of such a research effort in a rather broad frame.

Although the fusion programme provides also for the exploitation of alternative lines to the tokamak, it has been argued sometimes that the construction now, of a large facility like ITER might not be the approach with the lowest risk of failure. B. Villeneuve (CEA-Lemme) reflected on the effects of uncertainty on the evaluation of research programmes (with special interest in the fusion programme). The tragedy with ‘Big Science’ is that projects are not only

competitors in the sharing of funds, but it may also be the case that ‘the winner takes all’. This aspect, though defensible from the point of view of efficiency, seems to create a weakness in the sense that it cannot cope with the possible regret we could have in the end. However, there are pros and cons to flexibility. In general, flexible equipment is never ideal for the conditions of operations once they are known. Flexibility is a form of self-insurance in a situation where purely financial operation cannot be a substitute for technological solutions. Extreme flexibility, however, like a very generous insurance, is rarely desirable. In a way, the arguments in favour of flexibility are exactly the same as the arguments in favour of status quo (wait and see): we are at a maximum of flexibility when projects are *systematically* delayed, which makes no sense! Another important subject addressed in this study is the role of experts and expertise. Experts are an essential part of the democratic political systems. Citizens are not able to follow in detail all the debates. Delegation to experts is a compromise in the sense that an abandonment of sovereignty is accepted in exchange for a gain in time. The more difficult the matter, the more it seems it should be delegated, whereas very arduous questions often entail crucial decisions: even though the technical analysis is difficult, the consequences are so important that delegation to experts becomes hazardous.

At a given stage fusion power development and the introduction of this technology will become subject of a public debate and will require a political consensus. A group at the Institute for Technology Assessment and System Analysis in Karlsruhe provided an analysis of the Energy Consensus debate conducted in Germany in the early 90ies which involved the nuclear industry, the political parties, trade unions and environmental associations, and of the reasons of its final breakdown. The political scene is less frozen in its attitude regarding fusion, as was revealed, for example during an Energy Research Conference held in Greifswald 1997. A media analysis of the national newspaper reporting over the years 1993 - 98 revealed three main causes for reporting on nuclear fusion: the debate on ITER, the fusion power record obtained by JET in 97, and the start of construction of the Wendelstein facility in Greifswald. Assessing the political arena, the authors predict that alone the time-span of 50 years required for the commercial utilisation of fusion technology will be reason enough to refrain from assigning this option all too high priority, and to regard increasing need for support only with very great reserve. They see, however, a potential role of fusion as a pathfinder in increasingly globalised science, if it is able to integrate within an internationally accepted sustainable research and energy policy, and is also able to expand the structures of globalised system of research.

The European fusion research system itself was analysed in a study led by a group at Linköping University. This was conducted partly on a broad base, using questionnaires distributed to leading researchers in the field and bibliometric analysis, partly in the form of case studies singling out Germany and Sweden as respectively representatives for countries with a large effort, concentrated mainly in big institutes, and a smaller one, with research conducted mainly in a university frame. From the response of the scientists, the authors of the study noted in particular the following broadly held opinions and attitudes: a view that ITER will be difficult to manage due to complex international relations, confidence that scientific or technological problems do not pose serious obstacles, support of collaborations outside of Europe (particularly held by theoreticians), a reserve against more frequent evaluations of their research programmes, only weak support for research on inertial confinement fusion, but rather strong support for more research on alternative concepts of magnetic confinement, and the admission of a difficulty to justify fusion-related projects to non-fusion colleagues.

6 Conclusions and Outlook

The socio-economic studies carried out in the frame of the SERF programme of the European Commission during the years 1997-2000 have shown that power generation by fusion can become a cost-effective method to satisfy European demands for electric power in this century, if the need to stabilize the CO₂ content of the atmosphere is properly recognized. In the time frame considered, environmental concerns – and possibly concerns about the safety of supplies - rather than the total availability of primary energy will limit the employment of fossil fuels. Even rather moderate constraints on the CO₂ – budget allotted to Europe for this century would lead to a significant market penetration for fusion, limited in the scenario calculations essentially by the rate at which additional fusion power plants could be installed. The potential financial savings associated with the inclusion of fusion in such scenarios depend strongly on the assumed economic development and the stringency of the CO₂ constraints, but can under realistic conditions also approach 1000 B€ for Europe alone (discounted to 1998). Due to their very different capability to support base-load requirements, fusion and renewables do not appear in these studies as market competitors, but rather as suppliers for different needs of the market.

The estimations given here for fusion-based electricity production are based on physics assumptions and technologies, which are either proven, or constitute conservative extrapolations of the present state of art. The direct and external costs of fusion could be further decreased by bringing into routine operation the more advantageous physics regimes already attained in some experiments, by improving the performance of superconductors or their fabrication methods, and by proceeding to next generation structural and functional materials. Evidently these studies require a continuously updating of the economic input data for fusion, but also for the other energy sources and technologies.

Also the environmental properties of fusion are favourable, as measured by the external costs of the fusion power cycle, which are comparable to those of the best-performing renewables. In fact, the external costs for fusion found in the studies conducted under SERF1 and 2 were so low, that in terms of purely economic thinking, they would not merit further attention or efforts for improvements. Apart from this monetary value, results of externalities assessment are, however, a valuable parameter for measuring and optimising safety and environmental impacts. With this in mind, particularly the issue of C14 production, highlighted by these studies, will be addressed further. In the first effort, the corresponding source terms had been estimated very conservatively (i.e. large) to reduce the need for detailed calculations. More stringent calculations, which should result in reductions, have already been initiated. The production of C14 is also strongly dependent on the choice of coolant, breeding material and choices for structural or functional materials, and will be re- considered (and re-calculated) in conceptual power plant studies. Likewise, the accident studies, which resulted in very low cost estimates for the consequences of even extremely improbable beyond-design base accidents (80 M€), will be continued due to the high sensitivity of the issue. A caveat made by the authors themselves and a point of justified criticism to the comparison with other power supply systems was the use of present state technologies for systems competing with fusion, notably for coal and fission. This will be remedied in the next phase.

With large-scale commercial applications some 50 years in the future, fusion energy production and the associated benefits and risks are not yet a matter of public debate. These a-

priori expectations were confirmed also in empirical studies with structured interviews and focus groups. However, a broad support for continued research in this field was also apparent.

The public interest and involvement in fusion affairs increases dramatically, when the more imminent issue of the placement of a major fusion research facility in the neighbourhood arises. This was the case for Porto Torres, which in 1997 was considered by the Italian government as a possible site for ITER. A study was conducted there based on the “European Awareness Scenario Workshop” procedure, previously developed under the auspices of the European Commission, to promote the citizen’s participation in collective decisions concerning technology. It revolved around a structured discussion among 30 –50 people belonging to different social categories, and resulted in a strong involvement of the local participants and ultimately in an almost unanimously positive attitude towards the placement of ITER in their community.

The reported EU studies on socio-economic aspects of fusion were the first worldwide conducted with a similar width of scope. It has become apparent that SERF1 and SERF2 were only the start of a necessarily ongoing effort, which will need continuous updating not only to take into account the latest developments in fusion research, but also new information from other energy technologies. The two stages carried out so far naturally showed up needs for complementing, improving and further updating these investigations. This will be done in the SERF3 programme presently in its launch phase.

The SERF3 studies will be able to draw upon forthcoming results of the new Conceptual Power Plant Studies, which will provide consolidated input to the studies of direct costs, and the safety and environmental characteristics information needed for the assessment of externalities. Further studies on direct costs will concern the impact of potential physics and technology improvements, and the capability of reactors to adjust output to accommodate the contributions from intermittent power supply sources (renewables). A benchmarking of costing models and codes used in the different IEA countries will consolidate the worldwide basis of such estimates.

The economic scenario studies have so far been restricted to Europe, which in view of the world-wide nature of the CO₂ problem, and the need to share or to compete for resources, is justified clearly only as an intermediate step. The economic model (MARKAL) used in these studies is currently extended to a worldwide one (TIMES) in a collaborative effort in the IEA frame. Within the SERF3 studies, fusion will be included into this worldwide model. At the same time, the potential impact of fusion on one economic area with very different characteristics from Western Europe will be subject of a case study, in a collaborative effort with India. The long-term scenario studies have also revealed the inherent potential for synergy between fusion as base-load supplying and renewables as largely intermittent energy sources. These aspects will be further pursued by investigating technical aspects of such a combined system, including the stability of an electricity grid with such a supply mix.

The future sociological studies of SERF3 will have as their natural focus the possible siting of ITER in Cadarache, where the degree of public interest and hence also the knowledge on fusion will become high. The local debate will concentrate on ITER as a fusion research and demonstration facility, and on associated questions of public participation in such decisions. The enhanced visibility of fusion and the higher knowledge in the somewhat wider region around it will make this also the preferred site for studies of public attitudes towards more long-term questions like the preferences for the future energy mix and for the distribution of effort on energy research.