Socio-economic research on fusion (SERF) 1997-1998

Chairman's summary

1. Introduction and general overview

1.1 The origin of SERF

A successful fusion programme must lead to an energy source that is both economically and socially acceptable. As fusion approaches demonstration, these implications acquire major importance. Hence there is a need to complement the existing fusion knowledge basis with an additional track of research, that of socio-economic research on fusion (SERF). This was advocated by the 1996 Fusion Evaluation Board, chaired by S. Barabaschi, which prompted the Commission to consider the launching of a first programme of studies. It calls for a multi-disciplinary approach, bringing together researchers in the physical sciences, engineering, and the economic, social and environmental sciences.

1.2 Structure of SERF

Starting in October 1996, a number of experts on socio-economic issues and on fusion, proposed by the European Fusion Associations, met regularly within an ad hoc Working Group, first with the aim to identify possible elements for a first study on SERF to be concluded at the end of 1998, and then to follow up the general progress in the study. The composition of the Working Group is presented in annex 1.

The SERF programme 1997-98 (which was launched in July 1997) has been organised via Association contributions (micro-tasks), integrated in the following main areas of investigation (macro-tasks): SE0 - long term scenarios, E1 - production costs, E2 - external costs and benefits, S1 - fusion as a large technical system, S2 - fusion and the public opinion.
The list of all final association contributions to the SERF 1997-98 is presented in annex 2.

Every macro-task had some internal co-ordination among its participants, which had been provided by particular members of the Working Group. These macro-task co-ordinators have been responsible also for summarising the results of "their" macro-task, in the format of macro-task reports, which together with the present Summary form the SERF 1997-98 Report.

Overall co-ordination of the study and preparation of this Summary has been the responsibility of the Chairman of the Working Group, Professor Lars Ingelstam.
The Working Group has been assisted in its work and in its reporting by Dr Franco Cozzani of the Fusion Directorate.

Note: this Summary should, above all, be seen as a reading guide to the rest of the SERF 1997-98 reporting: Macro Task and Micro Task Reports. In these reports, numerous results are presented, but in most cases they cannot be condensed into a few lines, without impairing their accuracy and validity.

1.3 The relevance and the limits of SERF

The SERF programme 1997-98 has been successful in achieving a number of goals summarised in section 7. In view of the new content of the SERF studies, it could be surmised that the carrying out of a coherent, multi-disciplinary effort is a result in itself. The usefulness of an added "socio-economics dimension" to fusion R&D is now more widely recognised, among groups of researchers in the social and economics sciences. This would benefit both fusion, in providing a knowledge basis on broad issues of social acceptability, as well as economic and social sciences, in providing an added option for energy forecasting and a new, lively topic of research.

However, some inevitable limitations to this first round of SERF research must be noted. First, time has been short. For the execution of the research only 18-20 (calendar) months have been available (slightly more if we include some time for planning). Researchers that had not until then known more than the average citizen about fusion, had to pick up the basic knowledge fast. We notice that – by and large – the experts in the field have been very helpful and promoted this new line of work.

More serious, however, are the inevitable scientific and intellectual limitations. For socio-economic research the existing knowledge of fusion physics and technology has to be accepted as input, provided by the "fusion community". Major changes in the envisaged time-scale for a prototype reactor, failure to achieve envisaged technical targets or – on the contrary – unexpected breakthroughs, would alter significantly if not radically our conclusions. (Only at a later stage, could socio-economic results give guidance in researching different concepts and technical solutions in this difficult area).

Also in the sphere of social science theory and methodology, our research is limited by the "state-of-the-art". In some cases, the existing research paradigm is not particularly suited to fusion as an application. Three examples: (1) For the very long times to be considered in regard to investment and pay-back, conventional economic calculations such as compound interest may not be adequate. The research reported here has attempted to solve this problem by using different rates for intergenerational trade-offs and regular capital investment. (2) Some current research may be seen as "unfair" to fusion, whereas others adapt well to the particular properties of fusion (such as large scale). (3) For taking into account the particular properties of fusion and e.g. the

differences in risk between fusion and fission, a methodology such as ExternE (see section 4) may not be entirely appropriate.

Furthermore, some of the chosen methodologies encounter criticism (independently from their use in the fusion case) from some experts, and some of the underlying assumptions are open to debate. As social and economic research on fusion continues, different paradigms may emerge in some parts of the social and environmental sciences.

As a final remark, the SERF cannot provide "silver bullets" solutions to some of the challenges facing the development of fusion. Neither it should be intended as a public relation exercise, directly aimed at providing additional support for fusion.
However, it is worthwhile to stress how useful many of the results of SERF are for the fusion community at large. For example, social research can clarify possible obstacles to fusion acceptability by some sectors of the public, so contributing to identify errors to be avoided when interacting with the public and more refined ways to develop a dialogue on some issues. Also, results on scenarios and on economics could provide a more solid basis for arguing in favour of the potential advantages of fusion power and of its place in a future energy mix.

2. SE0 – Long term scenarios

2.1 Inputs and assumptions

Before the start of the SERF programme, fusion power has largely been neglected in long-term energy scenarios because:

- Fusion power is not likely to 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 CO_2 free and virtually inexhaustible power generation option. It is not obvious that fusion power could be more favoured in a high-demand driven scenario than in an ecologically driven scenario.

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. Their technical-economic characteristics are well known. Intermittent renewables - solar power, wind energy - are gaining importance. However, they cannot be regarded as solitary competitors to fusion power, which is a base load power option. Nevertheless, they could have considerable impact on the potential of fusion power.

Fusion power, presumed it would be technically feasible, has generally been assumed to have more impact for OECD countries than for developing ones. This assumption, however, needs further scrutiny.

Possible future concepts could be the 'Energy Amplifier' concept (a combination of a particle accelerator and a U^{233} breeder reactor, using Thorium as fuel), the 'MegaPower' Tower (using the temperature difference between sea level and at great height), and space-based solar power. 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. Two important notions are availability and geopolitical dimensions. Some discussed "advanced" renewables do not produce real base load power (the MegaPower Tower), whereas others (space-based solar power) would require power "relay" transmission from equatorial Africa, with its likely geopolitical complications, or lesser efficiency in direct transmission to Northern latitudes.

2.2 Expected cost ranges for fusion

The investment cost of a fusion power plant can be estimated, starting with first-of-a-kind fusion reactors (ITER-like) and estimating the effects of technical improvement (including larger unit size and multiple units at one site) and increasing numbers of plants (10th-of-a-kind, N^{th}-of-a-kind). Between about 2020 (DEMO) and 2050 fusion power is in the demonstration stage, and costs could come down rapidly. After 2050 cost digression is largely linked with increased numbers of plants: costs will come down slowly. Besides, technical learning will become insignificant for the part of the fusion power plant which is called 'balance of plant' (BOP).

Investment costs for Nth-of-a-kind fusion power plants in 2100 have been estimated in the range from 3000 ECU/kW to 4800 ECU/kW. The highest value pertains to a single 1000 MW unit plant, the lowest to a twin 1500 MW plant (i.e., 2 x 1500 MW units on the same site, sharing some common balance of plant). In the commercial stage, the major factors for the cost regression are unit size and number of units at one site. All values are in ECU 1995.

Power generation costs of different types of Nth-of-a-kind fusion power plants could be in the range of 70 to about 100 mECU/kWh. The lower figure pertains to a twin 1500 MW plant. Such cost figures have been derived from independent cost assessments, either collected or directly derived during the SERF programme.

2.3 Climate change

It has been demonstrated in the IIASA-WEC study of 1995 (and in other studies as well) that the rising CO_2 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.

Fusion is also deemed more expensive than currently available alternatives, such as fission power and coal-fired power. Therefore, fusion power (as other CO_2-free alternatives) would need some incentives like carbon taxes, to become "economically attractive". This is what has been investigated through a multitude of scenario calculations.

2.4 Scenario calculations

An updated MARKAL model for Western Europe, covering the years 1990-2100, shows that fossil fuels like coal are favoured for power generation in the absence of CO_2 policies. The Western European CO_2 emission would increase in 2100 compared to 1990, by 20% for the ecologically driven scenario Rational Perspective (RP) and by 60 % for the high-demand scenario Market Drive (MD), respectively.

Fusion power would be introduced at a significant level (120 GW in 2100), if the CO_2 emission would be stabilised in Western Europe in case of scenario MD; assuming that Europe contributes to 10 % of the world CO_2 emission, this case corresponds to a global CO_2 level of 650 ppm. In the same way, fusion power would be a significant power source in case of a slightly decreasing CO_2 emission in Western Europe in case of scenario RP; this case corresponds to a global CO_2 level of 550 ppm. Fusion power is introduced at the expense of coal fired power.

Sensitivity analysis shows that higher discount rates (8 or 10%) are not detrimental to fusion power, supposed fusion power has some market share due to CO_2 constraints in case of a 5% discount rate. This is because renewable power options - solar power and wind energy - 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 3000/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 (RP). This case shows that availability of oil and gas affects the competitiveness of fusion power. If a high potential for renewables and CO_2 sequestration technology is assumed, fusion power would face competition from coal fired power with CO_2 sequestration. A high potential of renewables is threatening to coal and gas fired power (450 ppm reduction case), but not to fusion power.

The role for fusion power is however sensitive to the assumptions for fission power. If a complete phase-out of fission power in 2080 is assumed, fusion power can profit somewhat in the case of a moderate CO_2 reduction target. If fission power is allowed to grow, fusion power is less prominent. However, it is still marginally attractive in the case of moderate CO_2 reduction (high-demand scenario).

A broad conclusion is that the long term potential of fusion power (in Western Europe) 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 CO_2 policies. However, if fusion power is not included in scenarios with CO_2 reduction targets, these targets can still be met but at a higher cost than with fusion power included as a technology.

3. E1 – Cost of fusion electricity

3. E1-Production Costs

The primary reasons for pursuing the development of fusion power are its anticipated safety and environmental advantages over alternatives for future base-load electricity generation, but it must also, of course, be economically viable. Prior to the SERF Programme, studies were made of projected fusion electricity production costs, and those were compared with published projections of the corresponding projected costs for fission, coal, and renewable sources.

Macro-task E1 of the SERF Programme carries this work forward. Work has been performed on: fusion power station systems modelling with much improved modelling of the physics; the benchmarking of cost extrapolations for fusion power stations; cost assessments of specific renewables; a wider economic characterisation of power generation options for the 21st century.

3.1 Plasma physics, technology and costs

In order to be ideally "attractive", a fusion power station concept should have major safety and environmental advantages, should be commercially attractive, and should be based on expected progress in plasma physics and technology. This section gives details of calculations, which explore the interplay between these factors. The work reported includes:

- Improved self-consistent modelling of fusion power station concepts.
- Calculations of capital costs, operating costs and costs of electricity, on different assumptions regarding progress in plasma physics and fusion technology.
- Calculations exploring uncertainties and potential cost/safety tradeoffs.

Fusion power station systems code analyses have been performed with a new code, embodying a more accurate, complete and detailed model of the plasma physics. The analyses took the form of revisiting the cases previously used as the basis for the

EURATOM/UKAEA Fusion Association's report to the Evaluation Board, plus additional calculations to explore further points of interest and uncertainty analysis.

The important results of the improved calculations confirm the important results in the previous work. The main conclusions are as follows:

- Overall costs, their dependence on the dominant parameters, and trends in the data, agree well with the earlier results from less developed and less comprehensive models.
- Fusion's safety and environmental advantages over alternatives for future base-load electricity generation are not compromised by economic optimisation of fusion power station concepts.
- The most important parameters driving fusion power station costs are the maximum possible normalised plasma pressure and the availability.
- The economically optimal power density is not high. Higher power densities, though lowering the volume of the device, produce more than compensating changes in plasma behaviour and replacement costs.

Based on the calculations performed, four reference fusion power station concepts are defined, chosen to serve as a suitable basis for scaling to a first demonstration fusion power station (DEMO). These are based on martensitic-ferritic steel as the structural material, the two blanket concepts being studied within the European fusion programme, and varying physics assumptions. A brief discussion is given of development tasks on the route to fusion, to introduce the consideration of a demonstration fusion power station (DEMO) and a first commercial fusion power station (PROTO). Using scaling arguments, targets for the costs and availability of PROTO and DEMO are derived. The main points are as follows:

- Between a tenth-of-a-kind commercial power station and PROTO, the main difference is in the capital costs of the fusion power core.
- Between PROTO and DEMO, the main difference is in the unscheduled unavailability (reliability).

An adequate treatment of availability, and of the dependence of component lifetimes on materials and operating temperatures, has not been included in this work: this should be a future priority.

3.2 Comparisons with advanced base-load alternatives

By taking recent cost extrapolations for fusion power from sources within and outside of the SERF-Project and benchmarking them with recent projections of investment cost of advanced alternatives for base-load electricity generation – fossil and fission power - a comparison of costs of electricity (COE) figures has been prepared. The selected alternatives are the European Pressurized Water Reactor, an advanced lignite fired steam power plant of novel design, two coal fired concepts: a supercritical steam

power plant and an integrated gasification combined cycle; and finally a natural-gas fired combined cycle. The comparison of the COE of fusion power with the COE of the alternatives, leads to following main conclusions:

- To achieve financial parity with the likely alternatives for base-load electricity generation, fusion power station construction costs would need to be about 60% of the projections based on current plasma physics and technology.
- The costs associated with component replacements (the costs of the replacements, and the restrictions on load following) should be lowered, by developing increased lifetime (neutron-resilient), low-activation materials and components.
- The alternative tokamak concepts "reversed shear" and "spherical tokamak" have very promising high physics performance and potentially better economic features than the ITER-like concepts. The latter seem to have physics limits to becoming economically attractive. But ITER could demonstrate the technical feasibility of fusion, as a forerunner of advanced fusion concepts.
- All other options for potential reductions in fusion investment costs, such as higher capacities than 1000MWe and multiple units at a site, should be pursued.
- Taxation of fossil fuels (and uranium) could support the financial viability of fusion. But the ultimate requirement is that fusion succeeds in being considered as a contribution to "sustainable development".

3.3 Cost assessments of specific renewables

Assessments have been made of the costs in mid-21st century of two non-base-load sources of electricity – wind power and solar photovoltaics. The crucial cost components were identified, their long-term evolutions were reviewed and assessed in the light of available studies, and estimates were accordingly made of the likely resulting costs of electricity.

It is concluded that a substantial cut in wind power cost per kilowatt-hour can be expected within the next 20-30 years. A survey of a number of long-term forecasts for wind power technology indicates a decrease in production costs of around 2-2.5% per year, implying that the cost of wind-generated electricity would be halved by the year 2030, probably making it competitive with conventional fossil-fuel-based electricity production.

Regarding solar photovoltaics, it is assessed that a substantial cut in cost per kilowatt-hour can be expected within the next fifty years, probably by a factor five by 2010, and that, somewhere between 2010 and 2050, solar photovoltaics will become competitive with fossil-fuel-based electricity production.

3.4 Power generation options for the 21st century:

Very extensive data are presented on a variety of power generation options for Western Europe, and used, together with fusion data generated in SERF Macro-task SE0, to calculate comprehensive figures for power generation production costs. The systems alternative to fusion included in the study were: light water reactors; a variety

of coal-fired, oil-fired and gas-fired concepts; hydro, wind, solar, wave tidal, geothermal and waste-to-energy concepts. The cost data are drawn from published sources and surveys. In deriving the costs of electricity, the levelised cost method was used, with discount rates of 5% and 8%. Power generation costs were calculated for the years 2070 and 2100.

It emerges from the study that at the close of the next century the likely production cost of electricity from base-load sources (fission and fossil fuel) is about 60% of the production cost of fusion electricity. The gap between the production cost of fusion electricity and electricity from photovoltaics at central or Southern European latitudes is small. The likely production cost of electricity from wind power may be comparable to that of fission or fossil fuels.

3.5 Conclusions:

These studies involve the great uncertainties of extrapolating many technologies, fuel prices, and other factors to future times varying from 2030 to 2100, and may have been performed with varying degrees of conservatism. Accordingly, the results of the various studies are not in precise agreement and should be treated with caution. Nevertheless, some overall conclusions can be drawn with a degree of robustness. These are stated below.

- Fusion power station systems code analyses have been performed with greatly improved models of the plasma physics. The results show the costs of fusion electricity in good agreement with earlier results from less developed models, increasing confidence in the analyses.
- Production costs of fusion electricity are likely to be higher – though not by a large margin – than the production costs of electricity from the alternatives (nuclear fission and fossil-fuel options) for base-load electricity generation.
- Production costs of fusion electricity are likely to be higher than the production costs of some intermittent sources, comparable to some intermittent sources, and lower than other intermittent sources.
- Production costs of some intermittent sources are likely to be comparable to production costs of nuclear fission and fossil - fuel electricity.
- In order to achieve acceptable financial performance, the essential primary requirements for fusion are:
  - To pursue concept improvements in the field of plasma physics,
  - To develop long-life materials and reliable components for the fusion environment. The materials must retain low-activation properties.
- Other options to reduce fusion costs, such as larger unit sizes and multiple units on one site, should be explored. Studies should be undertaken on how to assure high load factor.

It should be noted that the studies described in this report relate only to production costs: important economic factors have been studied elsewhere:

- Externalities: the external costs of electricity production by fusion, fossil fuels, fission and certain renewables were studied in Macro-task E2.
- Global constraints: the economics of electricity production from fusion, fossil-fuel, fission and renewables, subject to imposed global constraints on carbon dioxide and/or plutonium production, and the natural constraints on the proportion of electricity which can derive from intermittent or geographically limited sources, were studied in Macro-task SE0.

The ultimate requirement is that fusion succeeds in being considered as a contribution to sustainable development.

4 E2 – External costs and benefits of fusion power

4.1 Externalities of the fusion cycle

Choosing one energy option or another may have consequences on many aspects of society and the environment, which should be accounted for if we want to obtain the highest benefits for society. These consequences on society or the environment, which are not accounted for, are termed *externalities*. These are produced whenever production processes, or consumers' utilities, are affected by variables not controlled by them, but by other economic agents. This is the typical situation for energy use. Public health, agriculture, ecosystems, are affected by the use of energy by others, but are not compensated for that. The effects may be positive (external benefits) or negative (external costs) and their consideration may make some energy options more attractive than others in spite of their higher direct costs or vice-versa.

The technique of comparative risk assessment has traditionally been used in the *environmental* appraisal of different energy technologies. As an alternative, methods of monetary assessment of externalities have emerged. The work conducted by the European Commission (ExternE) and other bodies on monetary valuation have made this technique an useful tool in comparing the environmental performance of competing different energy supply options. However, the approach had not escaped criticism, and there is still a lack of confidence in this analysis by some researchers.

4.2 Assessing total environmental costs by the ExternE methodology

An assessment of monetarised external impacts of the fusion fuel-cycle has been performed using the bottom-up, site and technology specific methodology developed under the EC ExternE project. Two possible power plant designs (based on the SEAFP study) have been assessed with their main difference being the structural materials and cooling system used. These have been hypothetically located in Lauffen am Neckar, in south-western Germany. External costs of other energy generation technologies have also been assessed, in order to compare their external costs with

those projected for fusion. Several fossil fuel-cycles were considered as well as nuclear fission technology. Some renewable technologies were also considered.

- The external costs for fusion have been estimated to fall in the range of 0.4 – 5.4 mECU/kWh for Model plant 1 and 0.7 - 12.2 mECU/kWh for Model plant 2. These values are comparable to renewables (photovoltaic: 3.5 - 6.0 mECU/kWh; wind farm: 0.8 - 1.6 mECU/kWh), much lower than fossil fuel (oil: 51 - 78 mECU/kWh; coal: 30 - 55 mECU/kWh). The methodology yields 4.4 - 7 mECU/kWh for nuclear fission.
- External costs of the various alternatives may change as new technologies are developed and such costs are potentially avoided. Also, monetarisation has some limitations since some aspects are often left out, and some aspects may actually be difficult to monetarise. Nevertheless, the assessment of external costs for different energy technologies is in principle useful as it gives a common yardstick for comparison.

Applying the ExternE methodology to fusion electricity, many dimensions of external effects were evaluated in detail. The major impacts were identified as follows.

- For SEAFP Plant Model 2, the prevalent cause of external costs were the collective doses produced by the global dispersion of ^{14}C emissions (from activation in the reactor) as they enter the global carbon cycle and become widely dispersed throughout the world and liquid effluents of activation products. This is due to the use of water as coolant for this plant concept. These liquid effluents were not present in Plant Model 1 (which uses helium cooling), which also showed very reduced ^{14}C atmospheric emissions.
- Occupational impacts of the construction and decommissioning of the plant, and the impacts indirectly caused by the energy used on the manufacturing of materials were identified as other important causes of external impacts for both plant models. Total occupational damages were included.
- Impacts related to dust emissions from the recycling plant were also noticeable.
- The potential impacts caused by the waste disposal of radioactive materials from the plant would depend heavily on the assumptions made regarding the period of time when releases take place, but in any case nuclide ^{14}C seems to dominate the doses. External costs due to ^{14}C are incurred using long-term integration (10,000 years or more) of the caused dose impacts. Minimisation of nitrogen in structural materials would be a key factor in reducing externalities from fusion waste disposal.
- External costs produced by radiological accidents, normalised by the electricity generated by the plant and considering an occurrence probability of 10^{-7} per year were several orders of magnitude lower than the rest of the cost and they do not affect the final figure.
- An assessment of external impacts caused by the ingestion of contaminated foodstuff and water could not be performed in this study due to the lack of some crucial input data. Nevertheless, for Plant Model 2, the preliminary assessment

cause of collective doses, especially in densely populated areas as in the case of Lauffen area. Plant Model 1 does not present this type of impact. This aspect deserves further and more detailed analysis in the future.

- The assessment of the ingestion doses (due to routine plant operation) revealed that the location of a power plant is an important factor in the size of the impacts produced. In this case, the extremely elevated population density in the Lauffen area caused that, although individual doses were not high, the computation of collective doses yielded potentially high results. Location should therefore be included as a key variable in optimising future fusion plants design and installation.

Results from the cost benefit analysis of low activation materials (LAM) revealed that the development of LAM has some important benefits that could compensate the increased costs. Identified benefits are: reduced occupational exposure; reduced cost for waste management and disposal; reduced risk for accidental releases; and increased public acceptance.

4.3 The Porto Torres evaluation

Concurrently, an assessment of the economical impact of the possible installation of an experimental fusion reactor in the Porto Torres area (Sardinia, Italy) has also been carried out.

The direct economic impact of the construction and operation of a large fusion experimental reactor at Porto Torres is high, but perhaps not the highest among other possible economic interventions. The global economic impact could be maximised if the regional producers, particularly in the sectors involved in the installation, increase their integration (i.e., if the regional Leontieff multiplier increases above the 1992 value of 1.6). Activities such as the promotion of the (re)-qualification of the labour forces in the manufacturing and services sectors involved in the construction, and the promotion of joint ventures in the relevant sectors, are recommended.

As a topic for further investigation, the evaluation of the technological spin-off potential of a fusion experimental reactor on the local economy and the industrial sector is highly recommended as it might significantly modify economic activation and impact in the long term.

5. S1 – Fusion as a large technical system

5.1 A useful framework

”Large technical systems” has, perhaps not surprisingly, become a widely used concept, not only among engineers, but increasingly also among historians of technology and social scientists taking an interest in technology and science. A whole body of research shows that the ”technical” and the ”social” can not be strictly separated. In SERF we have found this approach appropriate for the study of fusion:

both as an elaborate and large-scale research effort (a ”large technical network”, sometimes referred to as *megascience*) and eventually as part of large technical systems of energy supply in the next century.

Social and technical complexity puts demands on the institutional and regulatory framework surrounding fusion, relating to issues such as proliferation, safety, energy supply, environment, industrial policy etc. In these fields, there is strong dependence on specialised knowledge, raising issues of understanding and transparency in governance. In particular, the potentially favourable characteristics of fusion need to be appreciated by decision-makers, often in quantitative terms, raising issues of reliance upon technical experts.

The main emphasis has been on the international and long-term character of research and development and the interplay between international and national research priorities. Work has been done also on the governance issues encountered in the national context.

5.2 The fusion research system

With a remarkable consistency, the fusion research effort is discussed, financed and implemented on a European level – and to a significant extent on a multi-continental basis (ITER and beyond). Research policies in participating countries have to work in harmony with priorities set on an international level. Through a broadly distributed questionnaire to research leaders in Europe, in conjunction with bibliometric analysis, document study and selected interviews, a picture of co-operation patterns, attitudes and opinions in the Associations has been obtained. One can find important differences in outlook from different Associations, which can partly be explained by size, research orientation and financing structure.

Among the results on attitudes and perceived obstacles, the following may be mentioned:

- many believe that the management of ITER will be difficult due to complex international relations
- scientific or technological problems do not, to most respondents, pose serious obstacles
- a solid majority supports the collaboration with countries outside Europe; theoretical researchers are the most convinced in this respect
- most researchers do not welcome more frequent evaluations
- support for more research on inertial confinement fusion is weak
- more research on alternative concepts within magnetic confinement has, however, a rather strong support
- fusion physicists claim to have a hard time in justifying their own projects to non-fusion colleagues.

5.3 Questions of governance

A related area of research in this task deals with political acceptance and policy vis-à-vis fusion. Evidently, the role of fusion in a public discourse (e g in the press) has a bearing on policy making and political decisions: in short what is often called ”governance”.

With Germany as one example, key actors in this process are identified, together with their strategies and their potential for consensus or disagreement. Political actors such as the major parties, commercial actors (with the nuclear industry in the lead), and trade unions are seen as actors. An attempt to achieve ”energy consensus” 1991-1993 failed mainly because of controversy around fission nuclear power. By studying the press and other public sources, it appears that fusion could not be disengaged as an issue from this background. However, the distinct differences between fission and fusion tend to be more clearly recognised. Also, the increasingly international collaboration of fusion research seems to be recognised as a decisive factor in terms of governance of this large technical system.

A related study, in fact a discussion paper, from the UK focuses on the safety and environmental potential of fusion and how this can translate into decision making of regulatory agencies and policy makers. Using a framework developed for other purposes (related to fission), one can arrive at a systematic array of issues. Regulatory concerns are primarily related to economic and technical issues and they should, according to the authors, be strongly favourable to the case of commercial fusion power stations. However, intermediate fusion devices are likely to be expected to meet high demands, being new and experimental. Policy making has to take into account a wider range of issues, such as perceptions of unfamiliarity, accidents, hazards and the technology being ”imposed” from above. The paper stresses that risk communication directly to the public or layman is complicated and can even be counter-productive.

For the case of Sweden, a debate of varying intensity has been going on over several years with political actors as well as researchers, in particular physicists, participating in it. Two elements deserve mentioning:

- for many of those opposing fusion research in the past, it seemed more or less a question of war and peace. Moreover, alternative sources of energy, such as solar and wind, were associated with peaceful world development. Evidently, there was a large gap of understanding between some parts of the public and the fusion research community
- presently, this perception of fusion seems to be gone. Instead the argument is put forward that the lead-time is too long, in order to solve rather pressing environmental problems. The issue is now whether the potential benefits of fusion can justify the large investment in research.

6. S2 – Fusion and the public opinion

6.1 Introduction

It has already been made clear that the future commercialisation of fusion power might be hampered by a lack of understanding and support by the public opinion. But it has also been pointed out that a research effort in this field should not be confused by a public relations effort on behalf of fusion energy or fusion research. However, there is a great deal to be known about public attitudes to modern, systemic technologies in general – and fusion power in particular. In this framework a workshop on the public acceptability of fusion power has been organised[1].

Fusion is not a hot issue among most sectors of the public. But there is in almost everybody's mind some link to fission nuclear power, which is recognised to be problematic. The more precise relation between them and the particular properties of fusion, such as its governance and time-lines, seem to be fairly little known. However this is not necessarily bad for attitude research. The various projects used different methodologies from the repertoire of behavioural and social science research. These attempts have to be considered more as a search for adequate methods rather than as final results concerning the questions mentioned. As stated above, fusion is not yet a matter of public debate. The object of research therefore is the opinion towards the ongoing process of fusion R&D or the opinion towards the construction of the ITER experiment.

6.2 Images and attitudes

In a study by CIEMAT, so-called "semi-structured" interviews were carried out, with several categories of people, in order to find out their evaluation of fusion in various respects.
Among interview subjects, persons were selected with a relatively good previous knowledge of fusion. Groups sought were fusion experts, fission experts, scientific journalists, environmental journalists and members of environmental movements. The results of the interviews were as follows.

Fusion was seen as an unlimited source of energy. Only the fission expert put less emphasis on this point. Risks were perceived, in particular due to tritium leaks and waste generation, but were estimated lower than for fission. All groups appreciated a diversified energy supply, while weights were put differently. Environmentalists favoured models largely based on renewables, the fission expert preferred those based on fission, the journalists and fusion experts favoured those based on fission and

fusion with some portion of renewables. All groups saw numerous technical problems of the fusion community to be solved. The fusion community was seen as a closed group. Information on fusion seemed to be scarce. Fusion might face the same fate as fission concerning the public attitude, which was at first in favour, while later turned to opposition. Some of the persons interviewed thought that the public would not have a fixed attitude towards fusion since it is a reality only in the far future.
High costs were expected for fusion. The high costs might disfavour fusion as a technique appreciated by the public.

6.3 Focus groups

Whereas the Spanish project made interviews with individuals the main tool, the group in Germany (Technology Assessment Academy in Stuttgart, on contract from Garching) worked with so-called focus groups. In this approach, a group is brought together and given rather short briefings on fusion (one in favour from a leading fusion scientist, one against it from a representative of an environmental organisation), on global energy projections and other energy sources. Then the participants in the group can interact with computer programs, discuss among themselves and demand further information. There are rather precise procedures to be followed when working with focus groups. The sessions are audio and video taped and will be transcribed in full. Each focus group consisted of six to eight persons. Groups were selected to have a broad spectrum of social and cultural backgrounds: managers, very young people (ages 15 to 18), science journalists, environmentalists, cultural elite, and science teachers. A second criterion was to find stakeholders that usually introduce a new topic into the public debate.

The cost/benefit ratio was a major topic in all groups. It was discussed who should pay for fusion research: public or industry. It was a concern whether there would be enough money to fund fusion together with alternative energy forms, such as solar, which the majority of the participants favoured as the desired option for the future. "Lifestyle" was the second major category. Here the discussion focussed on energy conservation as an alternative energy "source". In the extreme it was claimed that developing a new energy source would lead to unnecessary increase in energy consumption.

The issue of risk was discussed far less in all groups; two groups hardly discussed this topic at all. All groups realised that fusion will be less hazardous than fission. The nuclear waste was seen as the main risk, no discussion on accidents during operation took place. It was clearly differentiated between fusion and fission, although the preferred option was solar energy. A minor aspect of the discussion was the question whether the arguments given by the experts had been trustworthy or not. Most of the participants said that they were not able to make a judgement and that it was sometimes hard to decide on an issue.

The final discussion was introduced by the question: "Fusion as an energy option - yes or no?”

- The scepticism towards fusion was primarily motivated by the strong preference for alternative energy sources, in particular by the fear that fusion funding could take money away from the preferred technologies.
- Optimism was motivated by mainly two reasons: Fusion was seen 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 risk debate, which generally governs discussions on fission, was less emphasised here. The discussion mainly centred around the cost/benefit ratio topic.
- The global scope of the energy problem was hardly ever addressed in the discussions, in spite of the rather strong input stimulus on this topic.

6.4 Complexity, risk and democracy

In the Austrian sub-project several approaches were taken. The risk perception literature of the past decades has shown that understanding and analysing risk perception is a challenging task. Diverging socio-institutional risk perceptions are at the heart of controversies on many modern technologies. These risk perceptions are relatively immune to scientific evidence because they are grounded in divergent views on how to organise social, political and economic interaction. Insisting that risk perceptions are irrational, if they do not conform to expert assessment, is likely to deepen the controversy. Educating the public on how to perceive risk will fail.

As an example of a program to develop a large-scale technology, that of the German Liquid Metal Fast Breeder Reactor, was chosen. Lessons from this project, which failed to obtain public support, were seen to be relevant to fusion: for instance to avoid reinforcing distrust in the public towards authorities.

Not only the public's perception of complex technological systems, as described above, is of importance, but also the perception and evaluation by the involved experts themselves. This must include the necessary self reflection of science, in view of the danger that the experts misjudge the effect of their proposed technological solution on the ecological, socio-economic and political environment (unanticipated effects e.g. 30.000 policemen required for the transport of Castor spent fuel casks in Germany).

In order to evaluate the significance of nuclear fusion for long-term energy supply, it is seen as useful to set this energy option into the context of energy scenarios that have been developed for the 21st century. Therefore a variety of existing scenarios were analysed with respect to the specific role of fusion. In addition, a review of the criticism of the scenario methodology as such is given for example the dependence of their results on the input assumptions. The result is that fusion is only marginally mentioned in the well-known energy scenarios, such as those of IASA/WEC or IPCC, although some include general statements on fusion. This can, on the one hand, be seen as an expert judgement not in favour of fusion. On the other hand the widespread criticism of the scenarios reduces the weight of their results: the energy scenarios might have built in biases, which disfavour fusion. A rethinking of the position of fusion in energy scenarios is recommended.

Analysis of the frequently stressed terms centralisation/decentralisation suggested that the success of fusion will strongly depend on how future operational requirements of power plants can be fulfilled and how fusion will fit into future electricity supply systems - that is on the trends towards centralisation or decentralisation.

6.5 Experience in a European awareness scenario

A different methodology was chosen for the study in Italy. There a particular city was selected, with a long interesting history of industrialisation/de-industrialisation and a more recent history of public debates on various high-tech installations. In the project both these types of background were analysed thoroughly. This already gave some insight into opinion-formation, such as attitudes towards constructing a carbon power plant vs. the creation of a National Park. While such decisions were, by and large, taken in the past without informing or involving the public they have generated a background of negative public awareness of the issues.

As a second step, the research group then introduced, as a hypothesis, the building of a large fusion experimental facility in the area. Relevant information was given, and a process of discussion was initiated. Key groups were consulted, such as schools, political parties, financial institutions, industries, cultural associations, voluntary service associations and sports clubs. Then followed a process, structured according to an established methodology (European Awareness Scenario Workshop, EASW), in which broad options for the development of the area (with or without fusion) was discussed in fairly large groups (30-50 people).

As far as the social impact is concerned, the Porto Torres experience shows that in order to attain trust the local population has to be allowed to discuss as *experts* as actually they are the real experts of the territory they live in. Such a flexible approach also concerns the local actors that have a key role, not only as mediators. In particular, local administrators are the first interlocutors of the population because they are able to understand the reality they live in. With their help, instruments may be developed to enable citizens to take their own decisions and, most of all, to understand what kind of guarantees the citizens require about the discussion conditions and the actors involved. Discussion on fusion, as well as discussion on other new technologies, cannot avoid social conflicts. Our experience shows that, instead of facing or avoiding conflicts, it is possible to manage to make them productive in terms of social development.

The experience created a citizen network that is prepared to be kept constantly informed, updated and adjourned on the future developments. This would avoid stagnancy and subsequent setbacks of acquired learning, as well as stimulate the democratic process for decision-making. The attention of Porto Torres citizens towards fusion and high technology has become high, as well as willingness to engage in participation processes.

7. Concluding remarks

Overall achievement of SERF A network of economists and social scientists, integrated with fusion scientists, has been created and is now well established.
From a situation where fusion was absent from consideration in important domains of research and analysis, it is now gaining presence and attention. These domains are e.g. long-term scenarios for energy use, modern methods of accounting for externalities in energy systems, research policy studies, and scientific analysis of issues of perception of large and complex technologies by different sectors of the public.

Costing fusion Despite the long envisaged time-scale for fusion development, it is possible – and meaningful – to attempt to cost it. Experience from other technologies suggests that cost reductions are possible, due to learning curve effects. However, such curves depend on building and operating a number of plants, rather than time alone. Therefore fusion has to be accepted in order to become cheaper, like any other successful technology.

Fusion in the future energy mix The effect of CO_2 policies on the fusion share of the future energy mix has been clearly established by SERF: in order for fusion to enter the energy system, external costs of the fossil fuel cycles have to be accounted for. However, more extensive treatment of scenarios, where for example the energy use in various parts of the world is investigated, should be pursued.
Attempting to project "external" costs for different technologies over a long time-scale, one finds rather large difference in both estimates and uncertainty ranges. However, our results suggest that fusion (taking into account both direct and external costs, as well as external restrictions) could fall in the competitive range with other forms of electricity generation.
With regard to renewables, fusion would definitely not be in competition with them, but rather complementary; wind and solar energies would not be base-load options, at least in their presently envisageable form.

Fusion and the public opinion It seems difficult to interest much of the public opinion about fusion, as an energy option for the future. The very long time scale for its use is of course the main reason.
Direct contacts with sectors of the public (carried out through established social sciences methods) have however produced interesting points for reflection.
There seems to be no real opposition or a priori closure with regard fusion. Rather, there seems to be a diffuse lack of appreciation for the role of technical (or socio - technical) complex solutions to complex problems.

Possible major technology shifts It should be recognised that major technological shifts, inside or outside fusion, could radically change our outlook on the time-scale (or even the likelihood) of the introduction of fusion in the future energy mix. Examples could be: cost break-through in space-based solar energy with direct

illumination of northern latitudes, mega-towers or land based PV coupled to environmental- and energy- friendly electricity storage, new varieties of fission- based power plants, inertial fusion plants, magnetic or inertial fusion-fission hybrid systems.

Expanding the scope of a new SERF Many of the SERF studies suggest that analysis should not be restricted to fusion alone. Questions on "energy portfolios" arise in scenario work as well as in the investigations on public attitudes. The assessment of externalities should naturally allow comparisons between fusion and other energy sources. As mentioned before, existing methodologies have sometimes to be adapted to fusion (and other advanced technologies). A general conclusion is therefore that the SERF type of research should in part be performed in collaboration and dialogue with other research, development and evaluation regarding energy, environment and large infrastructure systems.

Without contradicting the above statement with regard to fusion, we also claim that the particular properties of fusion (long term, systemic, hi-tech, hi-science, a special safety and risk panorama etc) call for particular efforts and imagination in the field of social and economic research.

Diffusion of SERF results Socio-economic research of the SERF variety has proven meaningful and feasible. The dissemination and discussion of results deserves attention. Results from SERF and similar research should be made known, in the most appropriate ways, at least to four groups:

- decision-makers in research and energy policy
- the general public
- researchers and experts in fusion (the "fusion community")
- wider circles of researchers in the social sciences and economics.